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The Khmer did not live by rice alone: Archaeobotanical investigations at Angkor Wat and Ta Prohm

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ABSTRACT

The Angkorian Empire was at its peak from the 10th to 13th centuries CE. It wielded great influence across mainland Southeast Asia and is now one of the most archaeologically visible polities due to its expansive religious building works. This paper presents archaeobotanical evidence from two of the most renowned Angkorian temples largely associated with kings and elites, Angkor Wat and Ta Prohm. But it focuses on the people that dwelt within the temple enclosures, some of whom were involved in the daily functions of the temple. Archaeological work indicates that temple enclosures were areas of habitation within the Angkorian urban core and the temples and their enclosures were ritual, political, social, and economic landscapes. This paper provides the first attempt to reconstruct some aspects of the lives of the non-elites living within the temple enclosures by examining the archaeobotanical evidence, both macroremains and phytoliths, from residential contexts and data derived from inscriptions and Zhou Daguan's historical account dating to the 13th century CE. Research indicates that plants found within the temple enclosure of Ta Prohm and Angkor Wat were grown for ritual or medicinal use, and also formed important components of the diet and household economy.

1. Introduction

The Khmer or Angkor Empire dominated much of mainland Southeast Asia from the 9–15th centuries CE. The capital city was located near modern day Siem Reap in northwest Cambodia on the banks of the Tonle Sap Lake (Fig. 1). Angkor is famous for its massive stone temples that are the focus of tourism and are the most dramatically visible evidence of the Angkor civilization on the landscape. Although these stone temples are largely associated with Angkor's kings and elites, Khmer inscriptions from the Angkorian period also describe the lives of thousands of non-elite people involved in the daily functions of the temple, from religious specialists to communities surrounding the temple that provided food and labor to the temple operations (e.g. Coedès, 1906; Bhadri, 2007; Lustig and Lustig, 2013).

Temples played important roles in the Angkorian urban setting and most commonly they were centers of ritual and public performance tied to royal authority (Stark, 2015). Some temples were also places of learning; for example the temple of Ta Prohm was known as *rājvihāra* university (Coedès, 1906; Bhadri, 2007). Recent archaeological work indicates that temple enclosures were areas of habitation within the Angkorian urban core (Stark et al., 2015; Carter et al., 2018). Angkorian temples and their enclosures were ritual, political, social, and economic landscapes (Smith, 2014). The plants within temple enclosures were used by the Khmer for food, medicine and ritual, therefore plants were a key component of the Angkorian temple as an anchor on the urban landscape.

The current study examines archaeobotanical data from occupation areas and household contexts from Ta Prohm (henceforth TP) and Angkor Wat (henceforth AW) [Fig. 1]. This paper attempts to reconstruct aspects of the lives of the non-elites living within the temple structures through the analysis of botanical remains from residential contexts. Previous archaeobotanical studies in Angkor have mostly been palynological investigations (Penny et al., 2005, 2006, 2014, 2019) suited for understanding wider past environmental conditions.

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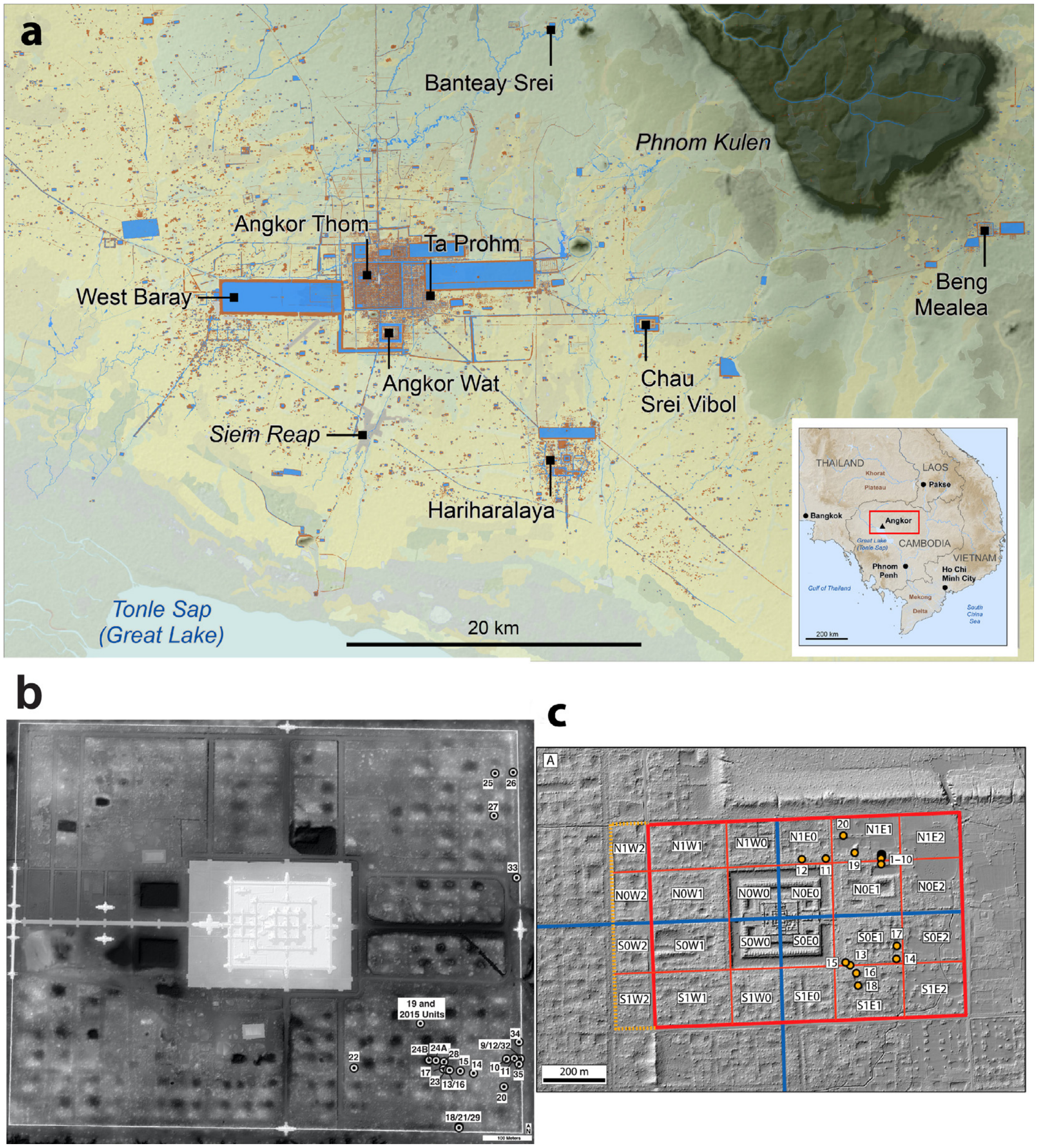

Fig. 1. a- Map showing the location of major temples and features in the Angkor region including the locations of Ta Prohm and Angkor Wat; Location of the trenches from where the archaeobotanical assemblages were sampled in b- Angkor Wat; c- Ta Prohm. Lidar images courtesy of the Khmer Archaeology Lidar Consortium (KALC).

As of today, the only published macrobotanical study of Angkor is from the site of the Terrace of the Leper King at Angkor Thom (Castillo et al., 2018a). However, those investigations focused on a ritual consecration deposit and post-Angkorian habitation areas within the Royal Palace at Angkor Thom dating to the 14th and 15th centuries CE when the elite abandoned the capital (Penny et al., 2019).

Both AW and TP appear to contain habitation areas of non-elite members of Angkorian society within their enclosures. The exact relationship between the inhabitants of the temple enclosures and the temples themselves remains unclear (Stark et al., 2015; Carter et al., 2018), however given their proximity to the temple, it is likely that some people who lived in the enclosures were among those whose labor kept the temples running. It is through archaeological studies and especially the botanical remains that we can begin to see traces of the lives of these people.

The results from the present study demonstrate the importance of plants to both the household economy, and the ritual functions of the temple. We refer to different sources to understand the use of plants by the Khmer. Some of the plants mentioned in Khmer inscriptions were identified in the archaeobotanical samples, such as rice, mung beans and long pepper. These plant remains would have been important components of the Angkorian diet and ritual and are mentioned in the inscriptions as donations to the temple. The micro and macrobotanical remains indicate the presence of household gardens, plants that were used for food and medicine, and plants associated with economic activities, such as cotton processing related to textile production and ritual activities of the temple. These results provide valuable insights into the identity of the Angkorian population, and also demonstrate the interconnectedness of domestic and household activities in these enclosures that were seemingly also related to the functions of the temples. There are also some patterns in the archaeobotanical assemblages of both temples, such as a higher occurrence of rice during the period of construction and occupation.

1.1. Plants used in temples: data from inscriptional evidence

Angkorian Khmer and Sanskrit inscriptions are important sources of information regarding the number of people engaged in the

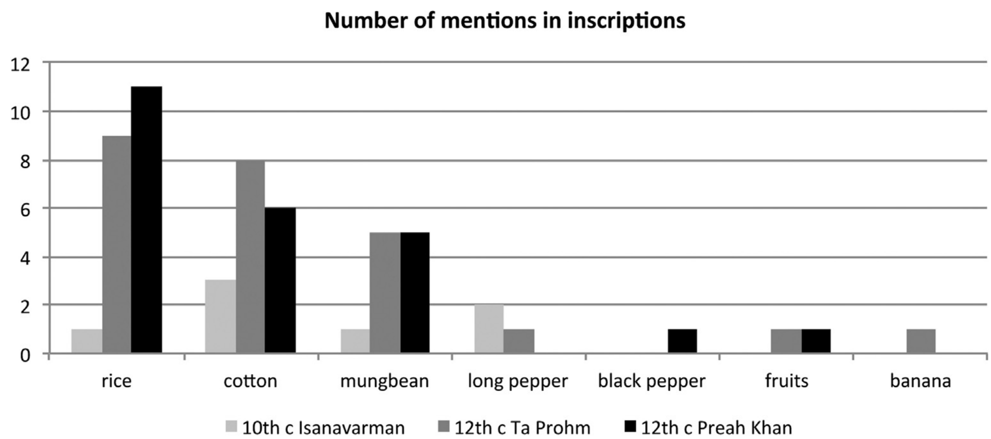

Fig. 2. Number of times a plant product found in the archaeobotanical record is mentioned in three inscriptions dating from the 10th to the 12th centuries CE.

maintenance and daily functioning of the temples, but also list the amount of goods, including plant products, donated and used in the temple. Here we refer to two inscriptions that provide some of the most detailed discussions of temple donations from stele at Ta Prohm (K. 273) and Preah Khan (K. 908), as well as a third recently translated inscription from the 10th century from Vat Phu, Laos (K. 1320). Rice is the most frequently mentioned plant product in two of three inscriptions studied (Fig. 2) and a key component of the Angkorian temple economy (Hall, 1985; Lustig and Lustig, 2015). Inscriptions indicate that rice was required as offerings to the gods and temple staff, with additional larger offerings required during certain holidays (Jacob, 1993: 281–282). An inscription from Preah Khan (K. 908) dating to the 12th century CE mentions rice as a necessity for ritual but also to feed the many people living within the temple grounds (Supp Table A). One can see parallels in modern Indian temples, where the rice is first ‘fed’ to the deities and then the ‘left-overs’ (prasáda) given to the servants of the temple or priests and the worshipers (Czerniak-Drożdżowicz, 2018). In fact, the Preah Khan temple grounds contained a rice storage house or ‘vríhigrha’, which shows the importance of rice for the daily servicing of the temple. The daily consumption of rice at Preah Khan amounted to ninety-seven kharís, three droças, and six prasthas, or 9340 kg following Maxwell's calculations (Maxwell, 2008; Supp Table A). This implies feeding one meal of approximately 85,000 people 110 g of rice a day. The Ta Prohm inscription (K. 273) mentions 79,365 people providing services to the temple (LXVII) and a requirement of 7302 kg of cooked rice daily (Coedès, 1906 LI: 28,040 khârî, 1 drona per year; see Supp Table B).

After rice, cloth is the other product with the greatest frequency of mentions in the three inscriptions and the most number of mentions in the 10th century CE inscription from Vat Phu (Fig. 2; Supp Table A). The frequency of cloth mentions indicates that textiles were important donations, a practice still seen in modern south India (Hacker, 2004; Goodall and Jacques, 2014). Textiles were probably used to clothe both the deities and the Brahmins, as is the case in modern Orissa, eastern India (Hacker, 2004; Goodall and Jacques, 2014) as well as for payment for land (Jacob, 1993: 285). The Ta Prohm stele inscription, also dating from the 12th century CE, more specifically notes the clothing needed for the gods and sometimes, the type of textile required such as wool or silk (Supp Table A).

Tantric Buddhist medicine flourished in Angkor during the reign of Jayavarman VII at the end of the 12th century CE when Tantric Mahāyāna Buddhism prevailed and resulted in the construction of a large number of hospitals (Chhem, 2005; Sharrock, 2009). Inscriptions describe the practice of healthcare within some temple structures although specific medicinal plants are not mentioned. The practice of medicine by the Khmer and the investment in hospitals during the late 12th century CE under Jayavarman VII's rule is well documented in the temple stele of Ta Prohm (Pottier and Chhem, 2008). The inscription at this temple specifically mentions rice (paddy) not only to feed the resident teachers and lecturers (XLV) but also for the sick (CXVIII). The Preah Khan stele mentions a ‘hospital’ associated with AW although it has not been identified (Pottier and Chhem, 2008). Ethnographic work has highlighted the importance of plants as traditional medicine in Khmer culture (see Martin, 1983). Inscriptions document aspects of daily Khmer life (Jacob, 1978) and also provide details that can be compared to the archaeological record.

1.2. *Greater Angkor Project fieldwork at Angkor Wat and Ta Prohm temples*

Fieldwork on occupation areas around temples was first begun as part of the Greater Angkor Project (henceforth GAP) in 2010 (Evans and Fletcher, 2015; Sonnemann et al., 2015; Stark et al., 2015). More recently, GAP fieldwork has benefited from lidar survey of the Greater Angkor region (Evans et al., 2013; Evans, 2016), which has highlighted a series of mounds, depressions, roads and pathways surrounding temple enclosures. Work by GAP has identified these as centers of habitation and extensive fieldwork has been undertaken in two temples: AW and TP (Stark et al., 2015; Carter et al., 2018, 2019). Excavations at TP were undertaken in 2012 and 2014, while excavations at AW took place in 2010, 2013, and 2015.

Multidisciplinary work was undertaken at the sites, including the recovery and study of macrobotanical, phytolith and geoarchaeological samples. The project included the environmental archaeological sciences as part of a collaborative project to further understand the habitation sites, such as the presence of gardens adjacent to houses and the household activities that would have been taking place. Macrobotanical remains analysis allows for specific plant species identifications and can provide information on the diet of the inhabitants, and crafts undertaken on a household level. Phytolith analysis complements macrobotanical studies when samples belonging to the same contexts are studied, but it is also useful in areas where plants were grown, stored, processed or disposed. Some plants, like domesticated bananas, may not result in macroremains but can leave a phytolith signature. In the case of some other economic crops, such as rice and foxtail millet, phytoliths are highly diagnostic of species and are useful in examining crop-processing stages taking place on-site. The geoarchaeological study concentrated on the mounds where houses were built and provides information on the site formation processes and domestic activities occurring in the settlement area.

Angkor Wat was built under the reign of Suryavarman II (reign 1113–1145 CE) and originally dedicated to the Hindu god Vishnu. However, Angkor and Cambodia were increasingly influenced by Theravada Buddhism beginning in the late 13th century CE with the

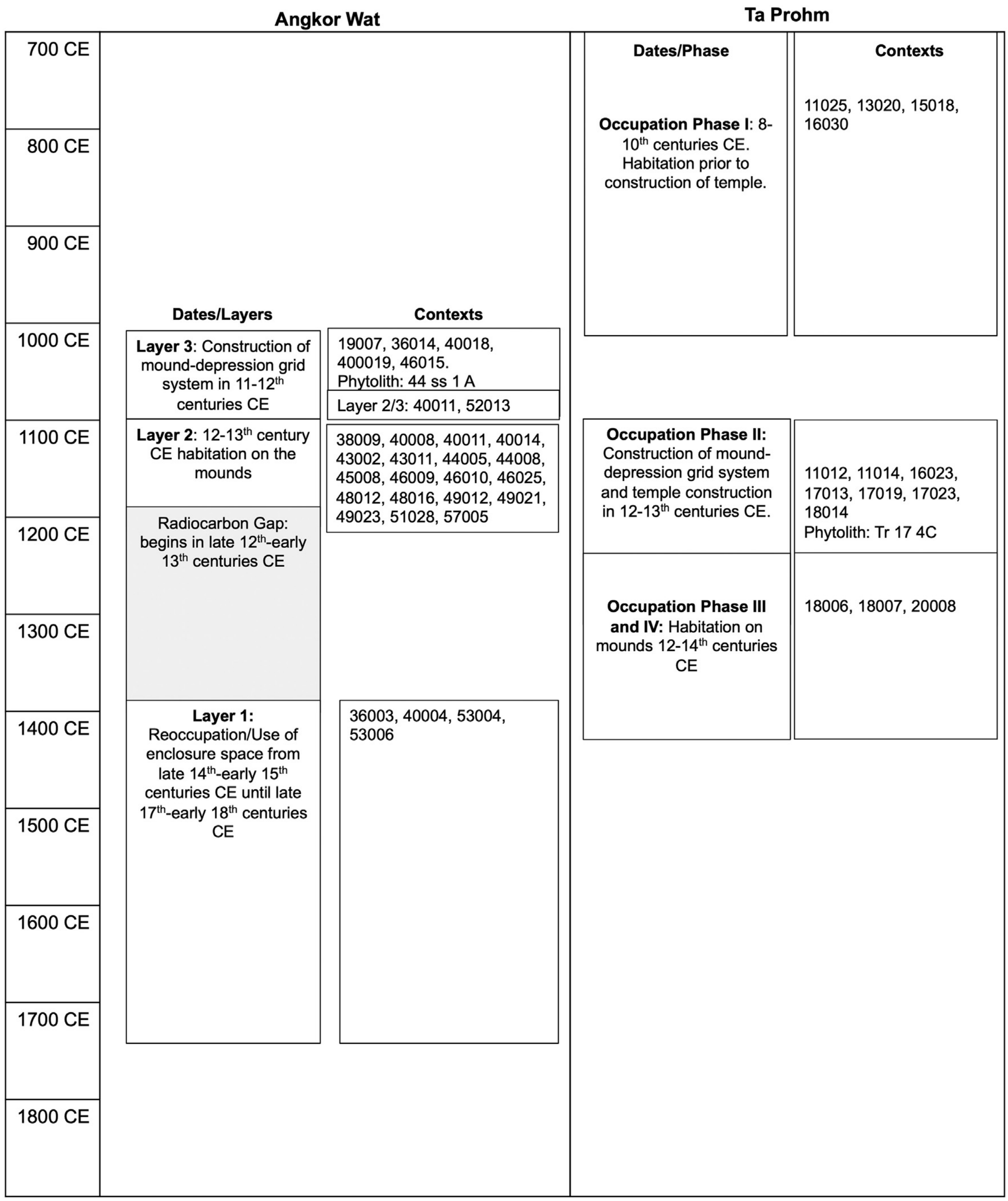

Fig. 3. Chronology of occupation and use of the Angkor Wat and Ta Prohm temple enclosures.

central shrine of AW transformed into a Buddhist sanctuary in the 16th century CE (Thompson, 2004). Three cultural layers were identified in excavations at AW (Stark et al., 2015; Carter et al., 2019; Figs. 3–4). Layer 3 marks the initial phase of modification in the landscape around what would become the AW temple in the 11–12th centuries. During this period, the landscape was transformed into the mound-depression grid system seen clearly in lidar images. The second cultural layer, which we date to the 12–13th centuries marks the immediate habitation on top of the mounds within the enclosure. Between Layer 2 and Layer 1 there is a gap in our radiocarbon dates that we associate with a transformation in the use of the enclosure space and perhaps an abandonment of the mounds. We argue that the most likely length of this gap is between 139–317 years, ranging from approximately the late 12th or early 13th centuries to the late 14th to early 15th centuries (Carter et al., 2019). Following this gap, there appears to be a reoccupation of the mounds beginning in the late 14th-early 15th centuries and lasting until the late 17th or early 18th centuries. This layer is associated with the Post-Angkorian period and is generally thinner and more bioturbated. We have proposed that the use of the mounds may have transformed during this period, with less intensive habitation and use (Carter et al., 2019).

Ta Prohm was built in 1186 CE during the reign of Jayavarman VII (reign 1181–1218 CE) and one of many temples constructed by this powerful and prolific ruler. Jayavarman VII practiced Mahayana Buddhism and built Ta Prohm in honor of his mother whom he represented as the Buddhist deity *Prajnaparamita*.

Multiple layers were identified in our excavations at Ta Prohm, which we have classified into four phases of occupation (Carter et al.,

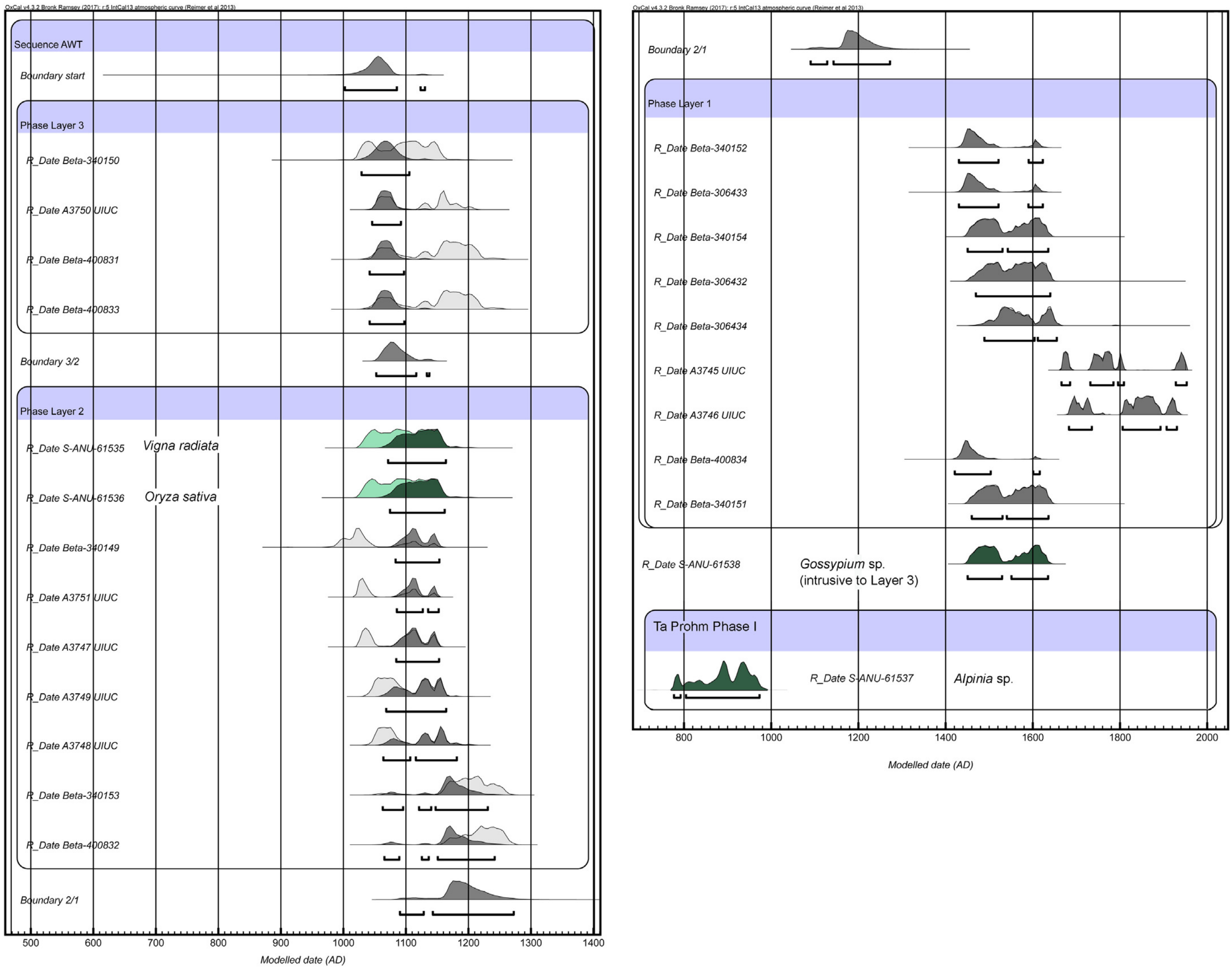

Fig. 4. Calibrated radiocarbon dates including the new dates from the macrobotanical remains at Angkor Wat and Ta Prohm in green, the date of the *Ziziphus buddhensis* seed was modern and not included. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2018; Fig. 3). Phase I dates to the 8–10th centuries and marks habitation prior to the construction of the TP temple. Phase II corresponds with the reorganization of the landscape and the construction of the mound-depression grid system in the 12–13th centuries. Phase III marks habitation on the mounds during the 13–14th centuries. The final Phase IV marks the upper layers of the mounds, which in some locations within the enclosure marks 13–15th century habitation or use of the mounds. However, no post-14th century ceramics were identified in any of our trenches suggesting the enclosure was abandoned during this period.

Five plant specimens from AW and TP were directly 14C dated (Fig. 4). The radiocarbon dates for the rice, mung bean and *Alpinia* seeds correspond to the expected dates for the layers where they were found, the date for cotton is later than expected and the boddhichitta seeds (*Ziziphus buddhensis*) found in AW turned out to be modern.

2. Materials and methods

2.1. Excavations

The soil samples were collected from the 2013 and 2015 excavations at AW and the 2014 excavations at TP under the direction of the Greater Angkor Project (GAP) in collaboration with the APSARA (Autorité pour la Protection du Site et l'Aménagement de la Région d'Angkor) Authority. Fieldwork at both sites took advantage of the available lidar data which identified a grid system of mounds and depressions within both temple enclosures (Evans et al., 2013).

The 2013 field season at AW saw the excavation of nineteen 1 × 2 metre trenches across the eastern portion of the fourth enclosure of AW on mounds, mound slopes, in depressions, and adjacent to the laterite enclosure wall (Stark et al., 2015). In 2015, excavations focused on the horizontal excavation of one mound within the enclosure, which had shown strong evidence for habitation during the 2013 field season (Carter, 2015). A total of twenty-two 1 × 1 and 1 × 2 metre trenches were excavated on the mound surface, slope, and associated depression. The goal of the 2015 field season was to better understand the spatial distribution of occupation activities on the mound and determine if areas on or around the mound may have been used for house gardens or horticulture.

The 2014 field season at TP centered on excavating ten 1 × 2 meter trenches across the eastern half of the enclosure, testing the various mound-depression configurations identified in the lidar data (Carter et al., 2018). This allowed us to determine if these various mound-depressions were areas of habitation and better understand the nature and timing of occupation within the enclosure.

Soil samples for macroremains, phytoliths and geoarchaeological studies, were collected from the mounds and depressions in AW. At TP, soil samples were collected from the excavations of mounds and depressions for macroremains and phytolith studies.

2.2. Geoarchaeology

Bulk sediments and thin section blocks were collected from the excavated trenches within the mounds and associated depressions at AW. The bulk sediments were collected at the same locations as the phytoliths using column sampling at an interval of c. 10 cm. The size and sampling location of the thin section blocks were determined based on the stratigraphic contexts during the excavation. Particle Size Distribution of the sediments were analysed at the Department of Geography, UCL, using Malvern Mastersizer 2000. Thin section samples were processed at the McBurney Laboratory for Geoarchaeology, University of Cambridge using the standard procedure developed by Charles French and Tonko Rajkovaca (French, 2015) and the slides were examined using petrological microscopes at UCL, Institute of Archaeology.

2.3. Macroremains

The methodology used in the collection and processing of soil is described in the Supp Data. A total of forty botanical macroremains samples from both sites were sorted and identified (Table 1). The results are reported and discussed in this paper. The list of identifications is found in Appendices A and B. Archaeobotanical soil samples from AW were taken from the 2013 and 2015 field seasons and an average of 9.1 l of soil per context was collected for flotation. A total of twenty-eight contexts were analysed. The soil samples from TP were collected during the 2014 field season and an average of 11.8 l of soil were collected for flotation. So far, twelve samples were analysed from TP.

2.4. Phytoliths

Phytoliths from AW were collected using column and bulk sampling. But at TP, the bulk soil samples set aside for flotation were subsampled for phytoliths. Samples were taken from habitation areas, including mounds and ponds. Phytolith extraction was done at UCL, Institute of Archaeology following the Rosen protocol (Rosen, 1999). A total of fourteen contexts from AW were processed and mounted and ten were counted and analysed (Table 1). At TP, six samples were counted and analysed. The preliminary results from both sites are discussed in this paper. The list of identifications is found in Appendices C and D.

3. Results

3.1. Geoarchaeology

Both sites display high levels of bioturbation as represented by the presence of modern roots, seeds and eggs (Supp Figs. 1 & 2). The high percentage of root material (≥40%) means that there is a high occurrence of bioturbation. Normally, bioturbation occurs in the upper layers and there is a correlation between the percentage of root material and modern seeds in a context. However, this is not the case in AW or TP. It appears that all layers, regardless of age, have relatively high levels of bioturbation with the exception of a few contexts (Supp Figs. 1 & 2).

The sedimentary sequences reconstructed through our detailed micromorphological and geophysical analysis of samples from the mound (Trench 36) and pond (Trench 44) represent different sedimentation processes that were associated with the construction, use and abandonment of the mound and related land-use practices in its surrounding area. The particle sizes and micromorphological features of the examined samples and their corresponding archaeological contexts are summarised in Supp Table C. The pond feature continued to receive eroded materials from higher ground in the surrounding area through multiple episodes of surface runoff events as evidenced by both the charcoal lens embedded in the sediments (Fig. 5a–b) and the typical colluvial material characterised by angular-shaped minerals in the groundmass (Fig. 5c–d). After it was entirely silted up, the pond experienced frequent wet-dry alternations. These resulted in the formation of dusty clay coatings with layered structures that are typically formed on disturbed surfaces with seasonal hydrological changes (Macphail and Goldberg, 2018) [Fig. 5c–d]. On the higher ground near trench 36, the surface was raised with earth dug from low-relief areas. This ground raising process is clearly indicated by the highly mixed groundmass present in the examined thin sections (Fig. 5e; Supp Table C). During the occupation of the mound, the surface remained relatively stable with some vegetation cover and light surface disturbance.

Geoarchaeological analysis undertaken in the mound and pond (after the pond was completely silted up) helps explain the bioturbation issue raised above. The groundmass of the examined samples from both trenches contained abundant organic matter, including charcoal, fine organic pigments and other plant remains (Fig. 5f). These were accumulated during the bio-cycling process of the rich biomass in this tropical environment and redeposited through surface geomorphological processes. Combined with dry episodes as evidenced by the presence of clay textural features and calcite coatings (see Supp Table C Tr. 36:3 calcite coatings and features) and relatively stable surface, this organic-rich, aerobic soil condition would have encouraged active bioturbation immediately under the vegetated surface. The most conclusive of severe bioturbation comes from the microstructural features. Granular,

Table 1
Summary statistics of the botanical remains.

	Angkor Wat		Ta Prohm	
	Macroremains	Phytoliths	Macroremains	Phytoliths
No. of samples floated/collected	85	113	68	53
Ave. volume of soil floated (l)	9.1	–	11.8	–
No. of samples analysed	28	10	12	6
NSP[a]	3903	–	1170	–
NISP[b]	1923	–	1120	–
Plant parts per liter MEAN	9 (± 9.47)	–	12.52 (± 24.28)	–
Plant parts per liter MIN	1.1	–	0.4	–
Plant parts per liter MAX	37	–	87	–
No. of taxa MODE	5	–	0	–
No. of taxa MIN	0	–	0	–
No. of taxa MAX	10	–	7	–

[a] Figures were interpolated (estimates based on fractional subsampling).
[b] Figures excluding modern plant parts & termite frass.

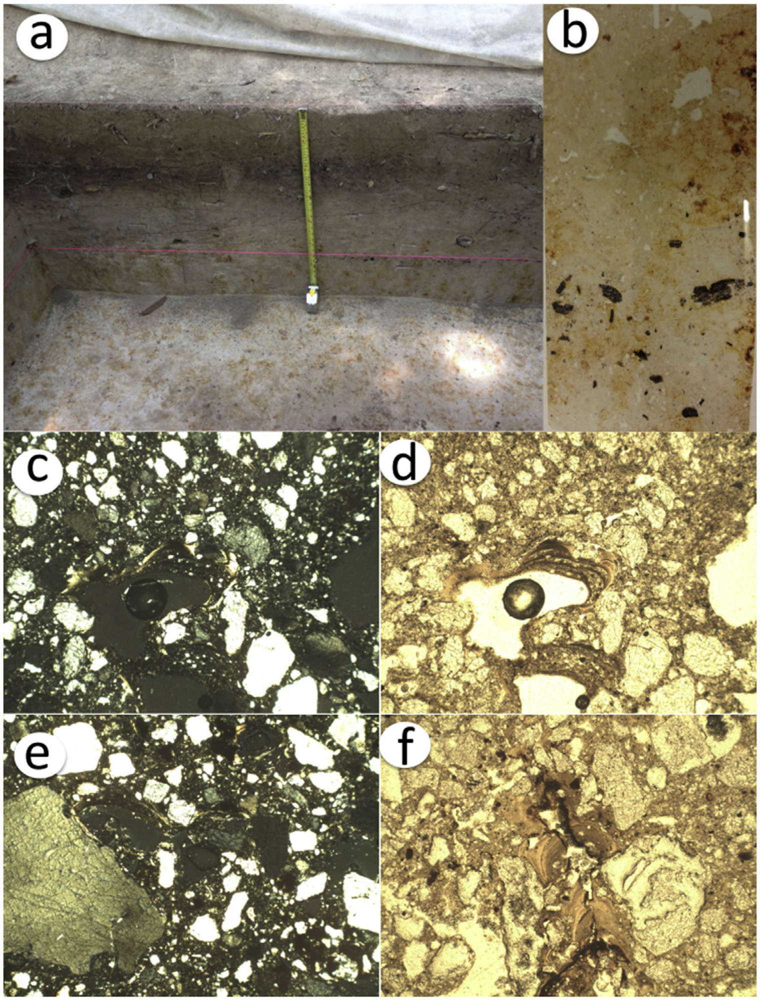

Fig. 5. a- charcoal lens just below the pink thread, excavation trench no. Tr. 44; b- thin section showing the charcoal lens in the pond, excavation trench no. Tr. 44 [10 × 5 cm]; dusty clay coatings with layered structure from sample Tr. 44–2, in XPL (c) and PPL (d). Also note the poorly sorted coarse sediments in the groundmass pointing to continuous colluvial events in the silting up process of the pond; e- highly mixed groundmass with abundant heterogenous materials, Tr. 36–4, XPL; f- groundmass rich in fine organic pigment (in this case, they are in silt-sized), Tr. 36–2; note abundant iron nodules and the also the disrupted clay coatings in the middle of the image. PPL. [images c,d,e and f are 2.8 × 2 mm]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

excremental microstructures caused by biological metabolism processes are commonly present in several thin sections (Supp Fig. 3). These granular microstructures often take up substantial space in the examined thin section slides (Supp Fig. 3), indicating that the bioturbation was common and of severe magnitude.

3.2. Macroremains

TP has more plant remains than AW showing an average of 11.7 plant parts per liter compared to 9 at AW, possibly indicating better preservation conditions of botanical remains at TP (Table 1). There are also more ceramics at TP than AW (Carter et al., 2018). However, there is greater biodiversity at AW where more taxa were identified than at TP. The largest proportion of plant remains in both sites is from unidentified seeds and seed fragments (Fig. 6). Both sites are made up of > 43% unidentified botanical remains, which is comparable to other archaeobotanical studies conducted in mainland Southeast Asia where the fragmentary nature of the archaeological remains is common (Castillo, 2013).

There were several economic crops found at both sites, most notably rice (*Oryza sativa*) and cotton (*Gossypium* sp.). Compared to TP, the samples from AW showed more species diversity. More plant parts from economic crops were identified at AW, such as mung bean (*Vigna radiata*), nut and fruit fragments including *Citrus* sp. rind, scarlet banana (*Musa coccinea*) belonging to the banana Family (Musaceae), crêpe ginger (*Cheilocostus speciosus*), black pepper (*Piper nigrum*) and long pepper (*Piper longum*). TP contained a larger proportion of wild or weedy plants (18%) compared to AW (3%). At AW, the 'other' category contains fruit and nut fragments (14% of NISP) whereas at TP, the contribution of fruits and nuts is negligible.

Archaeobotanical studies across Southeast Asian sites show that preservation issues exist and many botanical remains are fragmented. So even if only one or a few seeds of a particular species are identified, these are reported as important finds. This is the case in AW and TP, where some of the macroremains identified were discrete units but because of the dearth of archaeobotanical studies at the moment in Cambodia, these are considered relevant and are discussed below.

3.2.1. Rice (Oryza sativa)

Only two complete grains of rice were found in AW, the remaining rice remains were rice grain fragments, spikelet bases, an embryo and husk (Fig. 7a; n = 195). Rice plant parts make up 13% of the entire botanical assemblage whereas at TP, rice comprises 7% of the number of identified specimens (NISP).

In AW, only one spikelet base conformed to wild-type rice morphology and 99% were domesticated-type rice spikelet bases (n = 166). Similarly, 90% of the identified spikelet bases in TP were of the domesticated-type with a very low percentage of wild-type spikelet bases.

3.2.2. Mung bean (Vigna radiata)

Mung beans were only found in AW. A whole mung bean and a cotyledon were identified (Fig. 7b). The size and shape of the cotyledons and the length and placement of the plumule correspond to both modern reference collections and well-identified archaeological samples of mung beans (Fuller et al., 2004; Castillo, 2013). The two mung beans were charred, lacked the testa and are slightly smaller than the

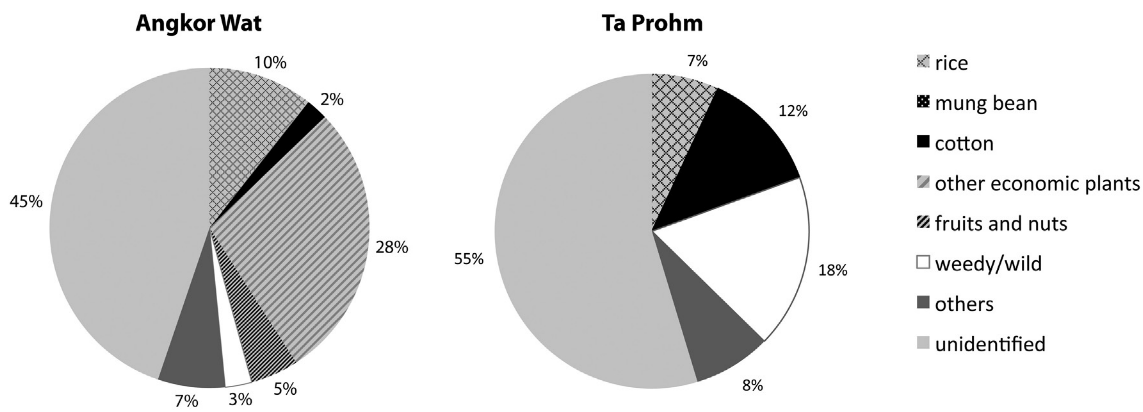

Fig. 6. Proportion of plant remains found in Angkor Wat and Ta Prohm.

modern counterparts as shrinkage occurs probably due to the effects of charring (Castillo, 2019).

3.2.3. Cotton (*Gossypium sp.*)

Cotton was found in 50% of the TP and 30% of the AW contexts sorted and analysed. One whole seed, funicular caps, seed and testa fragments were found in TP whereas at AW, only testa fragments and funicular caps were identified (Fig. 7c–d). Based on morphological features, it is not possible to differentiate between the different species of *Gossypium*, only identification to genus is possible. The testa samples from both sites contained the distinctive combination of irregular short cells and regular long cells (Vaughan, 1970; Fuller, 2008; Bouchaud et al., 2019).

3.2.4. Scarlet banana (*Musa coccinea*)

A 'scarlet banana' seed was recovered from AW. The seed was compared to reference banana seeds at UCL for size, shape and the pattern on the seed coat. The outer integument of the seed coat is smooth but has a pattern made up of minute lines extending from the micropylar plug. The micropylar plug was also compared to those of modern *Musa coccinea* and was consistent in its shape and size (Figs. 7e, 8a).

3.2.5. Costaceae family

Cheilocostus speciosus (J. Koenig) C.D. Specht (syn = *Costus speciosus* (Smith) Koenig) or 'crepe ginger' was identified in AW (Fig. 7f). The charred seed from AW was compared to modern reference collections and the dimensions and surface pattern matched those of *C. speciosus* (Fig. 8b–e). The Costaceae family is of pantropical distribution and yields rhizomatous herbs (Heywood et al., 2007). *C. speciosus* is found in moist and evergreen parts of India, Sri Lanka and Southeast Asia.

3.2.6. Piperaceae family

Black pepper (*Piper nigrum*) and long pepper (*Piper longum*) were identified in AW but not TP. The long pepper samples from AW were identified using the identification criteria for archaeological long pepper established by Castillo (2013). Although long pepper infructescences were all fragmented, identifications were possible (Fig. 7g). The black pepper fragment still retained its epicarp and was compared to modern black pepper fragments from the UCL reference collection (Figs. 7h, 8f).

3.2.7. Other economic plants

Fruits and nuts represent 10% and 7% of total plant remains at AW and TP respectively. Nut fragments, rind and mesocarp were identified in both sites.

The rind of *Citrus* sp. which has distinctive oil glandular patterns was found in six samples from AW (Fig. 7i). The *Citrus* genus contains oil glands throughout the plant, including leaves, stems and the rind. It is possible to identify some *Citrus* rind to species, such as pomelo (*Citrus maxima*), citron (*C. medica*) and papeda (*C. hystrix*) by examining the size and density of the pusticulae and overall surfaces as established in charring experiments using modern reference collections (Castillo, 2013; Fuller et al., 2018). The fragments from AW are leathery and have irregularly spaced pusticulae and although these have not been identified to species, they are not pomelo (Fig. 7i) but resemble either citron (*Citrus medica)* [cf. Kingwell-Banham et al., *2018*] or papeda (*Citrus hystrix*)[Castillo, 2013; Fuller et al., 2018; Fig. 8g].

Other economic plants found in AW are *Abelmoschus*, *Artocarpus*, *Dracontomelon* and Moraceae rind (Fig. 7j–k) and *Alpinia* sp. in TP (Fig. 7l). Identifications were made using modern charred reference material and descriptions of the flora. The *Abelmoschus* fragment contained enough features, such as the shape of the chalaza and the linear testa pattern surrounding the chalaza, to match it with modern *Abelmoschus manihot* var. *tetraphyllus* from the Institute of Archaeology reference collection (Fig. 8h–i), a traditional vegetable ("tree spinach") and fiber crop in Southeast Asia.

3.2.8. Weeds of rice cultivation

There are only a few taxa of weeds represented in both the AW and TP assemblages. Although these weeds (Supp Table D) are often associated with rice cultivation, they may also represent the surrounding habitats.

The weeds and rice co-occur in 46% of the samples at AW and 100% at TP but the weed biodiversity index is low in both sites. *Acmella paniculata* or para-cress, a weed associated with dryland rice cultivation in Southeast Asia is the predominant weed in both sites. However, the ecology represented by the weeds found in both sites cannot be properly defined since there is a mixture of weeds that thrive in both dry and wet conditions. More archaeobotanical work on rice from this period needs to be undertaken in order to fully understand the Angkorian rice cultivation systems. Was the rice being brought in from different regions, including nearby wetland fields and more distant dryland rice fields? Could this be one of the reasons for a mixed signal in the weed assemblage? Furthermore, the results from the phytolith analysis presented in the next section shows very little evidence for rice and as a consequence, discussions of associated weeds of cultivation is not possible.

3.3. Phytoliths

3.3.1. Angkor Wat

The phytolith samples from AW date to the 12–13th centuries CE, except for one (T44 SS1 A) which likely dates to the 11th century CE (Appendix C). The only evidence for rice within the phytoliths analysed at AW comes from the round white soil feature found near a

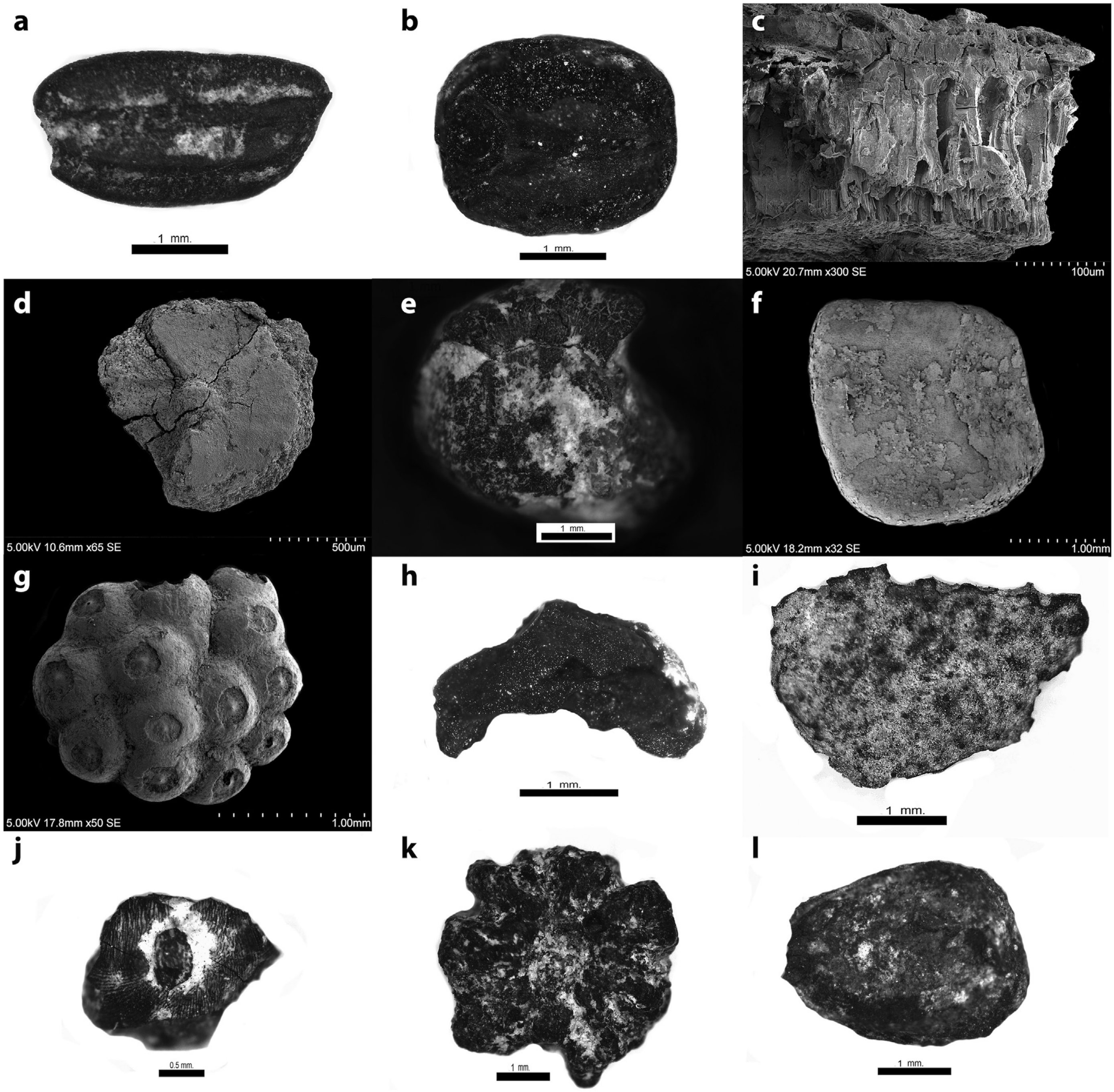

Fig. 7. a- rice grain (AW49023); b- mung bean (AW48016); c- cotton testa (TP15018); d- cotton funicular cap (TP15018); e- scarlet banana fragment (AW36003); f- crepe ginger (AW40004); g- long pepper (AW36003); h- black pepper fragment (AW40008); i- *Citrus* rind fragment (AW40004); j- *Abelmoschus* fragment (AW48016); k- *Dracontomelon* fragment (AW49021); l- *Alpinia* (TP15018).

concentration of sandstone (F 51028; Supp Fig. 4), which possibly represents an ashy deposit including burnt domestic plant waste. Other phytoliths found in the assemblage included the consistent presence of scalloped phytoliths, which occur in all but one sample at Angkor Wat and all but one at Ta Prohm. These are normally produced within the rind of Cucurbitaceae, suggesting the possible use of cucurbits at the site. There is also a consistent presence of volcaniform phytoliths, which are distinctive to *Musa* sp. leaves (Piperno, 2006). They occur in relative frequencies of 0.22–1.49% of Ta Prohm (1–6 counted per slide) and 0.25–0.82 at Angkor Wat (1–5 counted per slide) This low but consistent presence of banana phytoliths is indicative that the leaves were used, as this is where they are formed. However, it is highly likely that the fruits would have also been eaten, although these do not leave any macrobotanical trace when domesticated (i.e. *Musa acuminata* domesticates and/or *Musa* x *paradisiaca*). It is generally accepted that the Musaceae family produces distinctive phytoliths and the leaves produce genus-specific morphologies described as volcaniforms, troughs or truncated cones (Ball et al., 2006; Piperno, 2006; Horrocks and Rechtman, 2009). Trying to narrow down phytolith identifications to wild or domesticated status and to species is work in progress (Ball et al., 2006; Vrydaghs et al., 2009), and detailed morphometrics have not yet been attempted in the current Angkorian samples.

Spheroid echinate morphotypes are present across all the samples. These are distinctive to the Arecaceae family (palm), which includes

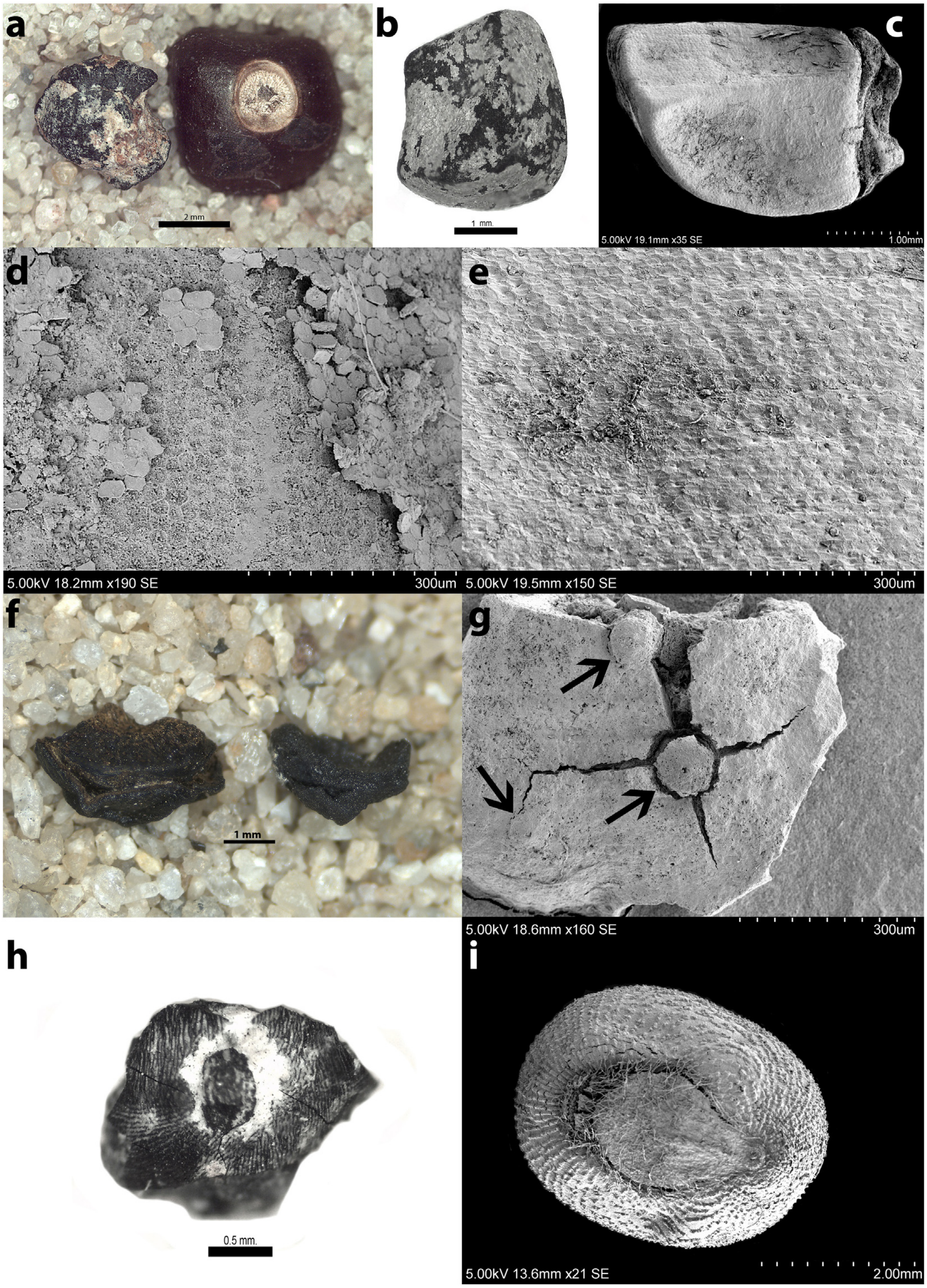

Fig. 8. a- archaeological seed of *Musa coccinea* (AW36003) compared to a modern seed; b- archaeological *Cheilocostus speciosus* (AW40004); c- modern *Cheilocostus speciosus*; testa surface of *Cheilocostus speciosus* d- archaeological; e- modern; f- charred modern black peppercorn fragment on the left and the archaeological fragment on the right (AW40008 at AW40018/2 bottom); g- fragment of *Citrus* sp. (AW36003), arrows show the spaced out pusticulae; h- fragment of archaeological *Abelmoschus* (AW48016) showing chalaza and testa; i- modern *Abelmoschus manihot* var. *tetraphyllus.*

coconut (*Cocos nucifera*), betel (*Areca catechu*) and toddy palm (*Borassus flabelllifer*).

The whole assemblage contains a consistent quantity of dicotyledon phytoliths (~25 of each sample; Supp Fig. 5). Many of these are associated with tree and woody species (e.g. sclereids, blocky, spheroid rugose). In general, dicotyledons produce significantly fewer phytoliths than monocotyledons, and this is again amplified when examining phytolith production in trees (e.g. Takachi et al., 2001). Taking this into account, the phytolith samples suggest that the flora of AW consisted of a significant quantity of trees and woody species. Such trees may have included *Canarium* sp., for which there is some evidence within the phytolith samples. A palynological investigation suggests mixed vegetation in Angkor from the 11th to 14th centuries composed of both dry forest and cultivated plants but no dominant taxa (Penny et al., 2019).

Table 2
Grass phytoliths classified by morphotypes.

Grass taxa	% AW phytolith assemblage	% TP phytolith assemblage
Rondels	41.46	40.39
Crosses and Bilobates	15.3	19.29
Saddles	5.97	8.88
Bilobates Tall	1.79	4.10

However, pollen from dipterocarps is present throughout the 11th to 14th century CE sequence; and considering their infrequent pollination event and general under-representation this indicates considerable presence in the landscape (Penny et al., 2019). This also strongly suggests that Angkor was founded within a largely wooded, tropical deciduous woodland, although open areas are to be expected in terms of natural clearings, and areas opened for agriculture and settlement.

In terms of grass diversity, there is a high quantity of rondels across all of the samples (1.7–6.2% of each sample). This is an unusually high frequency of rondels, which theoretically could be attributed to the use of a specific grass across the sites, for example for basketry or roofing materials. However, this supposition requires further study before any conclusions can be made. Rondels are present in many grass subfamilies, including Panicoideae [C4 Poaceae], Pooideae [C3 Poaceae] and Bambusoideae [bamboos] (Twiss et al., 1969; Mulholland, 1989; Table 2), but they are especially prominent on the inflorescences of tropical grass subfamilies including, Aristidoideae and Chloridoideae, and even some Panicoids (e.g. Barboni and Bremond, 2009; Novello and Barboni, 2015). This observation is consistent with grasses of wild savannah clearings, including many that favor fallow lands and unmanaged anthropogenic open areas.

3.3.2. *Ta Prohm*

The phytolith samples from TP date to the 12th century CE (Appendix D). The samples from TP contain a similar quantity of dicotyledon phytoliths to AW (Supp Fig. 6). At 37–51% of dicotyledon phytoliths, this indicates that the most of plant biomass around the site was trees, shrubs and weedy species, and not grasses.

There are spheroid echinate phytoliths in all of the samples, ranging from 0.58% to 4.46% of the total assemblage, indicating the presence of palms, which may include economic/cultivated palms as well as wild forest taxa. In addition, volcaniform morphotypes indicative of *Musa* sp. are present, ranging from 0.22% to 1.49%, which similarly may indicate cultivated bananas as well as wild taxa (also indicated by the seeds of *M. coccinea*). Other evidence for economic plants includes *Oryza*-type bulliform phytoliths, which are present in samples 16,023 4b/4 g, 17,019 3d and 17,023 3b/3d but at very low frequencies (1–3 single cells). Similarly, with the exception of sample 18,014 3b/4a (4 scalloped cells), 1–2 scalloped cells have been recorded from each sample suggesting the use of Cucurbitaceae crops.

As at AW, there is a high percentage frequency of rondels within the samples, indicating some open tropical grasslands or savannah clearing habitats, and possibly bamboo. While these could include cultivated plots the low occurrence of rice phytoliths suggests that these mostly do not come from harvested rice fields. Representative phytoliths found in AW and TP are shown in Fig. 9.

4. Discussion

The archaeobotanical assemblages from the two temples allow us to reconstruct some of the daily practices of the people living within the temple grounds such as what they were cooking and eating, but also potentially, a few of the plant products, such as cotton and bananas, processed on a household level to be used in connection with the temples. Many of the plants identified are crops which form part of people's diets, such as rice and mung beans, but are also prescribed as necessary for the proper functioning of the temples. We believe that given the contexts where the plant remains were found, we could identify their pathways.

In AW, 88.5% of the samples contained rice plant parts and at TP, this figure was slightly lower at 58.3%. Of all the botanical remains representing edible species, rice represents the largest proportion of macro-remains in both sites and was the main component in the diet of the Khmer and was also used to make rice wine called *bao-leng-jue* as witnessed by Zhou Daguan (Harris, 2007). In both sites, the high proportion of rice processing waste products such as spikelet bases and husk fragments indicates that rice was routinely dehusked where people were living since husk and spikelet bases are normally found in higher proportions than rice grains if they resulted from dehusking waste which went on to be burnt. Rice spikelet bases preserve well when charred and are highly visible in the archaeological record (Castillo, 2019), are good indicators of processing stages but also of the domestication status of rice in prehistory. Dehusking rice on a daily basis in a household is still practiced in Southeast Asia, such as at Ban Non Wat in Thailand (Castillo, 2019).

As expected in the historic period, the rice spikelet bases found in AW and TP indicate domesticated rice was cultivated. Domesticated rice has been cultivated in mainland Southeast Asia for at least 3500 years although the rice variety in the early prehistoric period was a different subspecies than which is cultivated today. The rice originally brought into mainland Southeast Asia from China was *Oryza sativa* ssp. *japonica* but today *O. sativa* ssp. *indica* is the main cultivar (Silva et al., 2018; Gutaker et al., 2020). It was only in the first millennium CE after a sustained period of contact with South Asia that *indica* rice was imported to Southeast Asia. Some rice assemblages from Late Iron Age Ban Non Wat (Northeast Thailand) suggest a minor presence of indica rice as early as the Fourth Century AD (Castillo et al., 2018b). In Cambodia, the only morphometric analysis of rice grains comes from Angkor Thom dating to the 14th and 15th centuries CE indicating the dominance of *indica*-type rice (Castillo et al., 2018a). Unfortunately, there are only two complete rice grains from AW and none from TP which does not allow for a morphometric study but one would expect *indica* rice to be the main cultivar in 12th and 13th century Angkor.

Rice at Angkor was not only part of people's diets, but it was also used in large quantities in ritual contexts such as in Angkor Thom in the 15th–16th centuries CE (Castillo et al., 2018a). Rice also formed part of offerings or taxes paid to the temples. As noted above, the inscriptions at TP and Preaḥ Khan mention paddy as offerings to support the temples (Supp Table A). A total of 28,040 *khârî* and 1 *drona* of rice per year are mentioned in the TP inscription, which amounts to 2,665,286 kg per year or 7302 kg daily. According to Zhou Daguan, rice was also used as currency, especially when it did not involve large transactions (Harris, 2007). The rice finds in the residential contexts at AW and TP were probably a result of cooking accidents.

Today, mung bean is an important upland crop in Cambodia (Bell et al., 2005; www.fao.com). It was domesticated in the eastern Ghats and/or the western Himalayas of India by the second millennium BCE (Fuller and Harvey, 2006). The mung bean was introduced into mainland Southeast Asia and was integrated into the Southeast Asian diet after its introduction in the last half of the first millennium BCE (Castillo et al., 2016). Together with rice, mung bean is the other main crop found in Cambodian historic sites, including at Angkor Thom (Terrace of the Leper King) and Preah Kahn of Kompong Svay (Castillo et al., 2018a; Castillo, 2020). Inscriptional evidence from TP and the nearby temple of Preah Khan include mung beans used in temple or ritual contexts (Coedès, 1906, Coedès, 1941; Bhadri, 2007; Maxwell, 2008; Fig. 2; Supp Table A). Like rice, the mung beans found at AW represent food items from cooking accidents. Their identification in AW indicates that both of these crops formed part of the diet and is evidence for cultivation and consumption during the Angkorian period. Although sesame and mung bean have not yet been found at TP, the TP inscription also refers to the presence of both plants at the temple site.

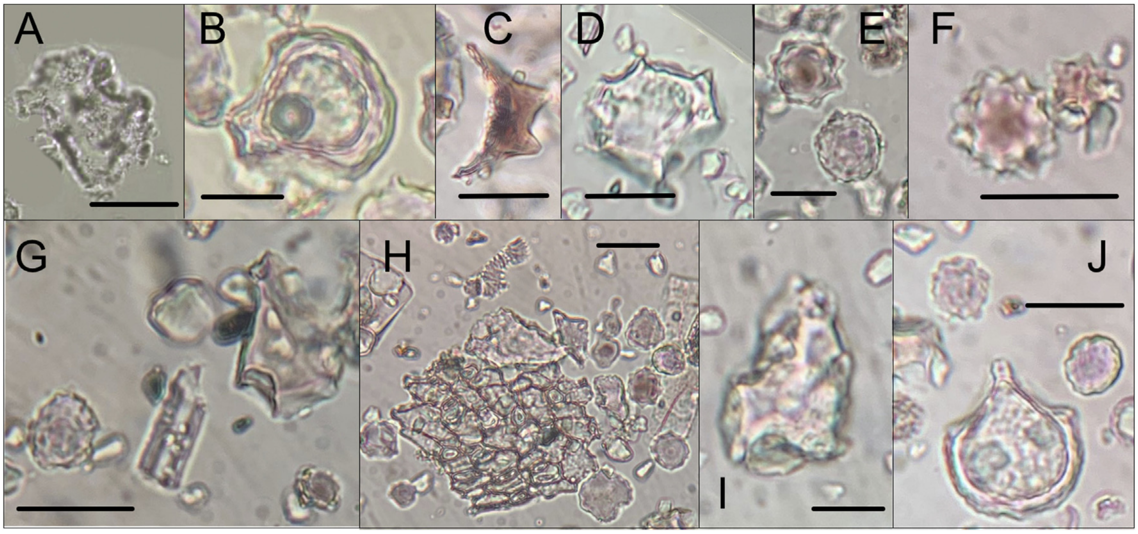

Fig. 9. a- *Musa*-type volcaniforms; b- *Oryza*-type bulliform flabellate; c, d- cf. *Oryza* husk; e- top: spheroid echinate bottom: spheroid rugose; f-Large spheroid echinate; g- *Musa* volcaniform and spheroid rugose; h- Tracheid, honeycomb/mesophyll layer and spheroid; i- Irregular polygon, woody dicot type; j- top: spheroid rugose and *Oryza*-type bulliform flabellate. Scale bars are 20 µm.

After rice and cotton, mung beans are the next most mentioned plant product in the inscriptions discussed here and in the 10th century CE inscription it is at par with rice mentions (Fig. 2).

Cotton seed fragments and funicular caps were found in AW and TP. This is significant as cotton seeds would be present only if the cotton bolls were brought to the site and suggests that craft production occurred. The lint or seed-coat hairs from the bolls were processed into fiber. Cotton has also been reported in another Cambodian site, the Terrace of the Leper King, dating to the 14th–15th centuries CE, and in the Iron Age Thai sites Khao Sam Kaeo and Ban Don Tha Phet (Cameron, 2010; Castillo et al., 2016; Castillo et al., 2018a). The cotton finds in TP outnumbered the rice remains. This may indicate that at TP, preparation of cotton bolls into fiber took place at a household level or alternatively, that the inhabitants in the TP temple enclosure undertook cotton processing. The lint would have been processed into fibers and the seeds discarded and burnt as garbage. Cotton represents 74% of the economic plant assemblage in TP from the 8th – 10th centuries CE, before the construction of the temple (Fig. 10). Although the proportion of cotton decreases in the next phases, it illustrates that cotton was still an important commodity.

Although cloth or garments are important items recorded in the inscriptions more often than any other non-food item (Fig. 2), activities related to cotton processing are not represented in any Angkorian reliefs (Green, 2000, 2003). Zhou Daguan (Harris, 2007) wrote that Cambodians did not use a loom but rather the backstrap loom to weave cotton:

> *'They do not use a loom for weaving. Instead they just wind one end of the cloth around their waist, hang the other end over a window, and use a bamboo tube as a shuttle* (Harris, 2007).'

Recent excavations at an Angkorian site in Battambang have identified spindle whorls, but none were identified in excavation contexts at AW or TP. Perhaps, the spindle whorls were made of wood and so have not preserved or they were not needed for the type of cotton present in Angkor. Spindle whorls can be made from pottery, stone or other material and heavier spindle whorls are normally used for material with longer fibers. It has been hypothesized by Castillo et al. (2018a) that Angkorians used tree cotton which grows into large trees and have short fibers, making spinning with a spindle whorl unnecessary. Zhou Daguan wrote that the Khmer did not spin yarn and instead used their hands to make strands (Harris, 2007). Based on historical parallels, we postulate that tree cotton was processed on-site, probably sourced from plants around field margins and settlement edges. Although cotton is not mentioned as such in the inscriptions, the term 'garments' is often used to denote cloth used to dress the images of the gods, and cover their thrones and their couches (Green, 2003; Maxwell, 2008). The inscriptions at both Preah Khan and TP record six hundred and forty-five and six hundred and forty sets of garments respectively in white and red for the gods (Coedès, 1906; Coedès, 1941; Maxwell, 2008). These pieces of clothing and garments are different from the 'silk' mentioned in the inscriptions and are most probably cotton garments. In India, textiles denote status and have often been associated with ritual, religious and political functions. In Angkor, Zhou Daguan writes that textiles were also used as currency, of higher value than cereals such as rice, but of less value than silver and gold (Harris, 2007). Angkorian inscriptions also suggest fabric/garments were frequently used for barter (Lustig et al., 2007).

The high incidence of cotton, particularly in TP, suggests that cotton was processed in workshops within the temple enclosure to meet the high demands for garments used in the temples. It is also possible that some of the cotton produced was meant as mementos to worshippers or pilgrims visiting the temples, a practice that continues to this day in the Jagannatha temple in Orissa (Hacker, 2004).

A few plants were identified from both macroremains and phytoliths, such as rice and *Musa*. The *Musa coccinea* macroremains from AW belongs to the banana family, an ornamental species with crimson flowers, but the leaves can be used as wrapping material and in the Pacific Islands, the plants are sometimes used as a living fence (Nelson et al., 2006). Wrapping food in banana leaves is commonplace across Southeast Asia. In Southeast Asia, banana plants are grown in temple grounds because they are considered holy (Piper, 1989). In south India, banana plants form part of Hindu ritual offerings or *puja* such as placing fried rice, jaggary, young coconut and banana fruits in a banana leaf tip known as 'Dooshan Ila' or the use of banana leaves as receptacles for flowers and other temple offerings (Pushpangadan et al., 1989). Discarded banana leaves used in ritual can make their way into the archaeological record and are visible in the phytolith analysis. Banana trunks, leaves, and fruits play a prominent role in contemporary Khmer rituals. *Musa acuminata* is used in the rituals, although in wedding ceremonies, other species/varieties can be used.

Banana plants (mainly *Musa acuminata* varieties and some *M. x paradisiaca*) were grown in 26,630 Ha of land across all provinces in Cambodia as of 2004 (SCW, 2006) and although this represents commercial plantations, banana plants are also found in people's backyards.

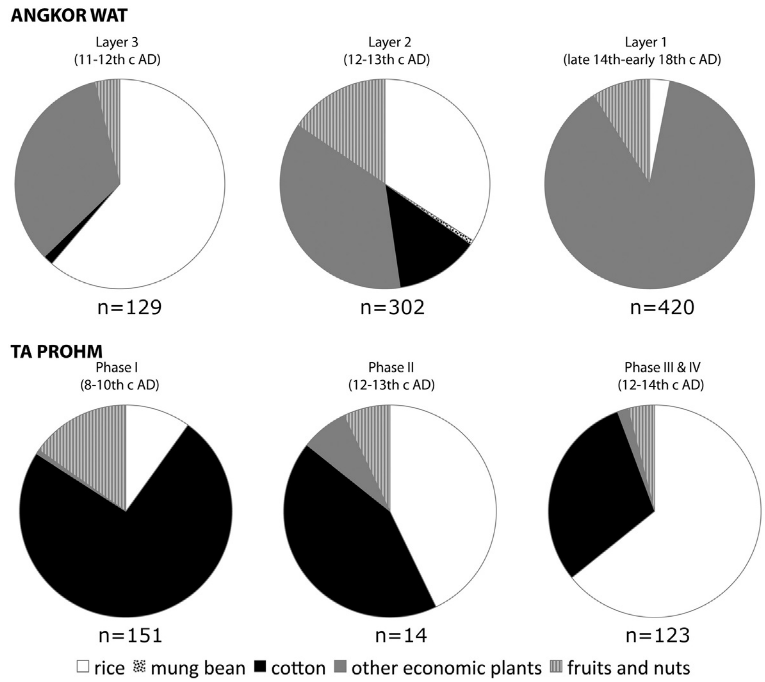

Fig. 10. Proportion of economic plant remains from Angkor Wat and Ta Prohm divided chronologically. Total frequencies per period are written under each pie chart.

The evidence for *Musa* in AW and TP indicates that bananas were planted in the home gardens and also the leaves were used as wrappers or animal fodder, and perhaps in a ritual setting as well.

Crepe ginger has been identified in AW. Principally an ornamental plant, it is also cultivated for medicinal purposes in India (Pawar and Pawar, 2014) and in Cambodia the rhizomes are used to assist births, and as a remedy against measles and smallpox (Dy Phon, 2000). The young shoots are also used in Cambodian cuisine to make 'sâmlâ' or liquid dishes (Dy Phon, 2000). Furthermore, in Vietnam, the roots of wild crepe ginger are gathered for medicinal use (Nguyen and Nguyen, 2008).

Piper is a large genus composed of 1000–2000 species and mainly found in the tropics (Tseng et al., 1999; Heywood et al., 2007). Several species are economically important including the familiar black pepper, and Indian long pepper. The origin of black pepper is the western Ghats, whereas for Indian long pepper it is the Indo-Burmese hills extending westward to the middle Himalayas [Kumoan] (Burkill, 1935; Dalby, 2002). The exact dates of the introduction of black and long pepper into Southeast Asia are uncertain. de Waard (1989) proposed that black pepper was introduced to Southeast Asia ca. 100 BCE although archaeobotanical evidence is still needed to confirm this date. Pepper that forms clusters and grows in a twisted vine is described by Zhou Daguan probably in reference to black pepper (Harris, 2007).

Long pepper is used principally for seasoning and as medicine. The treatise on Indian medicine Susruta Samhita dating to ca. 1st century BCE- 1st century CE records the use of long pepper as a medicinal drug (Atal and Ojha, 1964). Medicinal uses for long pepper have been recorded throughout historical times in South Asia such as in Shri Bhav Prakasha and Shankar Nighantu dating to the 14th century CE (Atal and Ojha, 1964). Long pepper is frequently listed in Angkorian period inscriptions to be used in a ritual context. Likewise, black pepper is used in traditional medicine in Cambodia. The Khmer Medical text known as "The treatment of the four diseases' manuscript mentions black pepper as an ingredient for nine medical recipes ranging from asthma to gonorrhea and long pepper once (Chhem and Antelme, 2004). The Preah Khan inscription lists black pepper as a donation from the royal storehouse (Fig. 2).

Palm tree phytoliths were also common in the assemblage and it is likely that these belong to coconut, areca and/or toddy palms. Although the phytoliths have not been narrowed to species, toddy palms were reported in palynological studies conducted in the West Mebon for the 15th century CE, from the nearby Bakong temple moat primarily for the mid 9th century CE and in Angkor Borei in the 7th century CE (Penny et al., 2005, 2006). According to Jacob (1978), coconut and areca palm plantations were donated to religious foundations during the Angkorian period. The fruits from these plants are also important offerings to the gods (Penny et al., 2005, 2006) Palm trees are a common sight across Southeast Asian landscapes and are also found in gardens.

A high quantity of dicotyledon phytoliths confirms the abundance of trees in the area. Likewise, the macroremains contain a large component of fruit and nut fragments. Fruit trees, such as the Southeast Asian domesticates durian and longan, are grown in house or village gardens alongside coconut palms and vegetables in Southeast Asia. Many plants found in Southeast Asian backyards are perennial, are low maintenance and provide yields all year round (Ho, 1995). This horticultural practice was probably similarly followed by the Khmer households.

In terms of preservation of botanical remains, the highest concentration of plant remains (30.4 plant parts /liter of soil) is the context described as a hearth in AW (40004). This context also contains the most number of taxa and although it contains some rice, it is mainly composed of economic plants and no weeds nor cotton. Edible plants (rice and traces of citrus fruits) are present but the majority of plants are fragments of those used as condiments, traditional medicine or in ritual (long pepper, crepe ginger).

What is clear from the archaeobotanical assemblage is that we have a good representation of plants that were grown in home gardens and also brought in from elsewhere. Fruit trees, long pepper, banana plants and palms are found in Southeast Asian home gardens whereas rice, cotton and mung beans are normally brought in from other areas.

Whilst the archaeobotanical evidence suggest, unambiguously, a vegetation assemblage related to horticulture or gardening practice near the excavation mound at AW and TP, results from our geoarchaeological investigation at AW are inconclusive. Gardening practices might involve hoeing or churning up and breaking up soil aggregates, manuring, and watering or irrigation. We have not yet found micromorphological features that might be associated with such gardening activities. The presence of abundant layered dusty clay coatings points to land clearance and surface disturbance as well as local hydrological changes, but it is unclear whether these resulted from farming activities and irrigation or other forms of land use practices. Multiple reasons might be responsible for the inconclusive geoarchaeological results with regard to gardening. Excavations focused on portions of the mound with evidence for household activities, therefore it is probable the exact spot where horticulture or gardening activities were taken place has not yet been excavated and therefore the samples we analysed only provide indirect evidence of related land use during the occupation of the mound at AW. We must also consider that post-depositional bioturbation has erased all the related evidence to horticulture, which has been confirmed in our results. Finally, Angkorian horticulture was an entirely different way of land use practice from modern horticulture or gardening practice. Given the limited excavations in Angkorian occupation contexts however, further investigation is needed to identify potential areas where household gardens may have been located.

A limitation of the study is the high level of bioturbation in both AW and TP. Bioturbation was evident in the soil profiles and in the macroremains analysis. However, it has been noted that many sites in Southeast Asia demonstrate high levels of bioturbation (cf. Castillo, 2013). One way to provide robust stratigraphy and archaeobotanical evidence is through radiocarbon dating of representative macroremains in each layer but this is expensive and therefore also a limitation. For our study, five plant remains were directly dated and the results are presented here (Fig. 4). The results indicate that the plant remains probably correspond to the layers where they came from most of the time, but we also have examples of intrusive remains.

According to the geoarchaeological study, there are a number of scenarios which might be attributable to post-depositional bioturbation at Angkor Wat. The excavated trenches were situated in vegetated areas surrounded by trees with deep roots which cause modern seeds to travel downwards from upper layers to lower layers. This might be another main cause of bioturbation in tropical environments. Some samples have a high proportion of modern hatched insect eggs, which also likely caused bioturbation. However, the factor which probably contributed most to bioturbation was the constant movement of soil by people as they rebuild and raised their living quarters.

5. Conclusion

Using archaeobotanical evidence together with information from inscriptions and Zhou Daguan's historical account, we provide a more complete depiction of the lives of the non-elites living within the temple enclosures. These data indicate that rice was the Khmer staple with a number of other economic plants represented consistently from Cambodian medieval sites, form the agricultural backbone of the Angkorian economy, including mung bean, sesame and cotton. Rice, although not found in vast numbers, is ubiquitous in both AW and TP. Cotton is heavily represented, as was also the case in Angkor Thom (Castillo et al., 2018a), and likely indicative of the importance of cloth in Hindu temple donations and ritual.

Nevertheless, there are some contrasting patterns found in the two temples. At TP, rice consumption increases over time whereas at AW rice consumption represents only 3% of plant remains after the 13th century CE (Fig. 10). Likewise, cotton is found in the first and second layers at AW but completely disappears after the 13th century CE. Perhaps this is related to a shift in the intensity of occupation identified at AW. Radiocarbon dates suggest an abandonment or reduction in habitation on the mounds from the 12th–13th centuries CE until the 14th–15th centuries CE, when the mounds were reoccupied although less intensively (Carter et al., 2019).

In contrast, cotton processing appears to be most important at TP prior to the construction of the temple, but is present throughout the different phases (Fig. 10). This pattern is also paralleled in the evidence coming from the three inscriptions studied. In the 10th century CE, cloth has the biggest number of mentions but declines over time when compared to rice (Fig. 2). At AW, the highest diversity in plant products occurs during the Angkorian period when the temple was founded and in use, representing the period when people were most intensively living within the temple enclosure. After the 13th century CE, although plant remains show the site was still inhabited, there is less diversity in the use of plant products possibly due to reduced ritual functioning of the temple. This trend is not seen in TP which although it has less diversity in plant remains, use continues up until the 15th century CE. It could be that the mounds excavated in TP form part of households dedicated to craft specialization, such as cotton processing.

In general, the plant diversity suggests both cultivation in the surrounding area (of food crops and cotton trees) and probable garden cultivation in and around the city and temples. The bright-flowered *Musa coccinea* likely graced spaces within the city as indicated by the presence of macroremains and *Musa* phytoliths. Leaves used as containers and mats also contribute to the *Musa* phytoliths. Whilst cultivation of edible bananas is likely, it cannot be proven without species level identification it is likely that edible, seedless domesticated bananas were grown. Other components of urban gardens are likely to have included a number of palms (coconut, *Areca* and toddy palms) and spice plants like long pepper and crepe ginger.

Thus, Angkorian cities must have been tropical gardens, actively cultivated and harvested, as well as being the sites of monumental state construction. But plants within the temple enclosure of Ta Prohm and Angkor Wat were grown not just for ritual or medicinal use, but formed important components of the diet and household economy. Furthermore, gardens were a key component of urban planning and may have allowed for greater food security for city residents (Isendahl, 2012; Barthel and Isendahl, 2013; Stark, 2014). The study of macro- and micro-botanical plant remains gives a picture of wholistic daily life in ancient Angkor.

Declarations of Competing Interest

None.

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Appendix A. Angkor Wat macroremains

Species	36003	36014	38009	40004	40008	40008 at 40018/2	40011 Clay spit	40011 Posthole	40014	40019	43002	44005	44008	45008
Volume of soil before flotation	10	5	8	8	10	3	2	3	8	9	8	10	9	1
Plant parts/Liter of soil	37	9.4	1.4	30.4	7	16.7	1.5	4.7	4.8	1.6	14.1	6.5	2.8	7
No. of taxa	5	1	1	10	6	6	0	3	5	2	6	4	1	2
ECONOMIC PLANTS														
Oryza sativa														
Oryza sativa fragment			1			1					1			
Oryza sativa sb – domesticated	1				1	5		1	5		5			1
Oryza sativa sb – wild											1			
Oryza sb – ind.				4	2					1	1	1		
Oryza – immature fragment														
Oryza carbonised frag w/husk														
Total rice	1	0	1	4	3	6	0	1	5	1	8	1	0	1
Vigna radiata														
Vigna radiata fragment						1								
Total pulses	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Gossypium sp. funicular cap											2			
Gossypium sp. fragment										2				
Total cotton	0	0	0	0	0	0	0	0	0	2	2	0	0	0
Cheilocostus speciosus				1										
Phyllanthus emblica seed												1		
Ziziphus buddhensis				2										
Ziziphus buddhensis fragment				64										
Musa cf. *coccinea*	1													
Piper nigrum frag. w/epicarp						1								
Piper longum fragment	300	43		66	14	6			2		75			3
cf. *Abelmoschus* fragment														
cf. *Artocarpus*														
Total other economic plants	301	43	0	133	14	7	0	0	2	0	75	1	0	3
FRUIT AND NUT PARTS														
Nut shell – prob. *Lithcarpus*														
Rind														
cf. *Citrus* rind	15			12	6				2					
Fruit pedicel					1									
Fruit/nut frag. indeterminate														
Mesocarp (fleshy fruit)				2				4						
Moraceae rind with mesocarp														
Moraceae														
Nut cotyledon frag – poss. *C-astanopsis*														
Dracontomelon sp. fragment														
Nut shell													7	
Total fruit and nut parts	15	0	0	14	7	0	0	4	2	0	0	0	7	0
WEEDY/WILD														
Acmella paniculata					1									
Acmella paniculata fragment								1	1					
Mikania cf. *cordata* fragments					7				2		1			
Commelina diffusa														
Isoetes trilete spore														
Total weedy/wild	0	0	0	0	8	0	0	1	3	0	1	0	0	0
OTHERS														
Rhizome detachment scar				1										
Juncus sp.														
Wild rice														
Thorns				5										
Grass culm node												1		
Fabaceae cotyledon fragments														
Fruit unidentified				2										
Ovary or bud and pedicel														
Asteraceae											1			
Lateral rootlet of tuber; prob. Cyperaceae											1			
Silicified Euphorbiaceae em-bryo	2			4										
Root				3										
Buds											4			
Parenchyma										1				
Cooked food														
Total others	2	0	0	15	0	0	0	0	0	1	6	1	0	0
Total unidentified	51	4	10	77	38	36	3	8	26	10	21	62	18	2
NISP	**370**	**47**	**11**	**243**	**70**	**50**	**3**	**14**	**38**	**14**	**113**	**65**	**25**	**7**
NON-BOTANICAL/MODERN														
termite frass														1
fungal sclerotia		105												
modern	99	12	1	264	25	8	7	2	3	4	118	4		

coprolite								1	1		110	2	6	3
resin	2		2		4									
eggs modern	90	7		87	23	6	20		28	1	292	51	2	8
Total non-botanical and modern	191	124	3	351	52	14	27	3	32	5	520	57	8	12
NSP	**561**	**171**	**14**	**594**	**122**	**64**	**30**	**17**	**70**	**19**	**633**	**122**	**33**	**18**

Species	46009	46010	46015	48012	48016	49012 Bag 2	49021	49023	52013	53004	53006	57005	19007.01 Jar A	19007.01 Jar E	
Volume of soil before flotation	10	10	19	11	12	10	13	13	10	1	4	10	4	1	222
Plant parts/Liter of soil	3.3	2.1	10.1	2.1	12.3	4.3	2	12.8	1.1	28	13.5	4	12.5	21	9
No. of taxa	6	5	4	3	7	3	5	5	3	7	5	4	3	2	
ECONOMIC PLANTS															
Oryza sativa								1					1		2
Oryza sativa fragment			6		2			4			3		4		22
Oryza sativa sb – domesticated	6	6	40	4	6	10		10	3	1	2	8	11	3	129
Oryza sativa sb – wild															1
Oryza sb – ind.	8		1		4	8					2		4		36
Oryza – immature fragment				1											1
Oryza carbonised frag w/husk			4												4
Total rice	14	6	51	5	12	18	0	15	3	1	7	8	20	3	195
Vigna radiata					1										1
Vigna radiata fragment															1
Total pulses	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2
Gossypium sp. funicular cap					2			2				4			10
Gossypium sp. fragment	4				1	2	4	12				6			31
Total cotton	4	0	0	0	3	2	4	14	0	0	0	10	0	0	41
Cheilocostus speciosus															1
Phyllanthus emblica seed															1
Ziziphus buddhensis															2
Ziziphus buddhensis fragment															64
Musa cf. *coccinea*															1
Piper nigrum frag. w/epicarp															1
Piper longum fragment	1			4						1					515
cf. *Abelmoschus* fragment					1										1
cf. *Artocarpus*					1										1
Total other economic plants	1	0	0	4	2	0	0	0	0	1	0	0	0	0	587
FRUIT AND NUT PARTS															
Nut shell – prob. *Lithcarpus*	1														1
Rind					1		1			2					4
cf. *Citrus* rind									1		1				37
Fruit pedicel															1
Fruit/nut frag. Indeterminate		1						11							12
Mesocarp (fleshy fruit)					10					5		1			22
Moraceae rind with mesocarp							3	1							4
Moraceae							1								1
Nut cotyledon frag – poss. *Castanopsis*											1				1
Dracontomelon sp. fragment							1								1
Nut shell															7
Total fruit and nut parts	1	1	0	0	11	0	5	12	1	7	2	1	0	0	91
WEEDY/WILD															
Acmella paniculata	1		6			2		2							12
Acmella paniculata fragment		2	12			2		2					1		21
Mikania cf. *cordata* fragments															10
Commelina diffusa			4												4
Isoetes trilete spore		1									2				3
Total weedy/wild	1	3	22	0	0	4	0	4	0	0	2	0	1	0	50
OTHERS															
Rhizome detachment scar							1								2
Juncus sp.									1						1
Wild rice		1													1
Thorns															5
Grass culm node	4									1		2	1		8
Fabaceae cotyledon fragments				3											3
Fruit unidentified															2
Ovary or bud and pedicel			1												1
Asteraceae															1
Lateral rootlet of tuber; prob. Cyperaceae															1
Silicified Euphorbiaceae embryo											2				8

Root				1											4
Buds										2					6
Parenchyma					50					1			22	1	75
Cooked food	2				1						4				7
Total others	6	1	1	4	51	0	2	0	1	4	6	2	22	1	125
Total unidentified	6	10	117	10	67	19	15	122	6	15	37	17	7	17	831
NISP	**33**	**21**	**191**	**23**	**147**	**43**	**26**	**167**	**11**	**28**	**54**	**38**	**50**	**21**	**1923**
NON-BOTANICAL/MODERN															
Termite frass															1
Fungal sclerotia															105
Modern	1	1	4	7		2	2	5	26	98	237		3		933
Coprolite			5		2	16					8				154
Resin		7		1	6	1								3	26
Eggs modern	42			15	9	71	1	6	1	14	28				802
Total non-botanical and modern	43	8	9	23	17	90	3	11	27	112	273	0	3	3	1981
NSP	**76**	**29**	**200**	**46**	**164**	**133**	**29**	**178**	**38**	**140**	**327**	**38**	**53**	**24**	**3903**

The bold numbers represent totals.

Appendix B. Ta Prohm macroremains

Species	11012	11014	11025	13020	15018	16030 Bag 1	16030 Bag 2	17013	18006	18007	18014	20008	
Volume of soil before flotation	7	5	5	13	4.5	5	10	20	10	15	14	23	132
Plant parts/Liter of soil	7	5.6	0.4	9.5	87.1	0.6	1.6	3.6	21.7	10.7	1.5	1	150
No. of taxa	5	2	0	7	7	0	0	4	6	8	3	3	
ECONOMIC PLANTS													
Oryza sativa fragment									1	3			4
Oryza sativa sb – domesticated	1	2		3	2			1	6	22			37
Oryza sativa sb – wild										3			3
Oryza sativa sb – immature	1												1
Oryza sb – ind.										8			8
Oryza lemma apex – awned									24				24
Oryza husk fragment				7	2				8	1			18
Oryza charred embryo										3			3
Total rice	2	2	0	10	4	0	0	1	39	40	0	0	98
Gossypium funicular cap	1				23								24
Gossypium seed without testa					1								1
Gossypium frag	3			1	87			2	32	5			130
Total cotton	4	0	0	1	111	0	0	2	32	5	0	0	155
Alpinia sp.					1								1
Total other economic crops	0	0	0	0	1	0	0	0	0	0	0	0	1
FRUIT AND NUT PARTS													
Mesocarp				3	19			1	1		4		28
Nut shell – prob. cf. *Lithocarpus*					1								1
Total fruit and nut parts	0	0	0	3	20	0	0	1	1	0	4	0	29
WEEDY/WILD													
Acmella paniculata	25	13		80	4			20	18	6	1	5	113
Acmella paniculata (0.5–1 mm)										8		10	77
Fimbristylis cf. *dichotoma* silicified									8				8
Commelina benghalensis silicified												1	1
Diplacrum caricinum				1	2								3
Total weedy/wild	25	13	0	81	6	0	0	20	26	14	1	16	202
OTHERS													
Poaceae culm node				1					32	2		1	36
Rhizome detachment scar				1									1
Rind – prob. *Euryale*	1									2			3
Small charred tuber	1								1	20	1		23
Small Panicoid										1			1
Parenchyma										3			3
Charred cooked food				14									14
Total others	2	0	0	16	0	0	0	0	33	28	1	1	81
Total unidentified	16	13	2	26	250	3	16	47	86	74	15	6	554
NISP	**49**	**28**	**2**	**137**	**392**	**3**	**16**	**71**	**217**	**161**	**21**	**23**	**1120**
NON-BOTANICAL/MODERN													
Rice husk impression on pottery	1				1								2
Modern	3	3		8						12		1	27
Fungi sclerotium								1					1
Resin	1							4	1	1		2	9
Shell										1			1
Coprolite				1						3			4
Bone				6									6
Total non-botanical and modern	5	3	0	15	1	0	0	5	1	17	0	3	50
NSP	**54**	**31**	**2**	**152**	**393**	**3**	**16**	**76**	**218**	**178**	**21**	**26**	**1170**

The bold numbers represent totals

Appendix C. Angkor Wat phytoliths

Archaeological feature	Charcoal/ceramics concentration 12–13th C AD		Round white soil feature 12–13th C AD				Soil discoloration/pit? 12–13th C AD			Depression "pond" early phase of mound construction 11th C AD
Sample number	F43011 SS1	F43011 SS2	F51028 SS1	F51028 SS2	F51028 SS3	F51028 SS4	F46025 SS1	F46025 SS2	F46025 SS3	T 44 SS1 A
Elongate entire	15.93	12.17	16.63	10.60	11.568	9.89	9.23	19.71	11.34	11.81
Elongate sinuate	0.00	0.00	1.20	0.54	1.028	0.00	1.58	2.00	0.30	0.48
Elongate dendritic	0.74	0.00	0.24	0.27	0.257	0.00	0.79	0.00	0.00	0.24
Elongate dentate	0.00	0.00	0.00	0.54	0.771	0.00	0.53	0.00	0.00	0.24
Crenate	0.00	0.29	0.48	0.27	0.000	0.28	0.00	0.86	0.00	0.24
Acute bulbous hair	5.88	5.80	6.51	7.07	5.398	8.47	6.86	11.14	6.57	5.54
Papillate	0.49	0.00	0.48	0.54	0.514	1.41	0.00	0.00	0.00	0.00
Bulliform	1.47	0.29	1.45	2.17	1.028	1.69	0.53	0.29	0.30	0.96
Bulliform flabellate	0.98	0.87	1.45	1.90	1.285	1.69	1.32	0.86	1.79	1.45
Oryza-type bulliform flabellate facetate	0.00	0.00	0.24	0.00	0.257	0.00	0.00	0.00	0.00	0.00
Bilobate	0.25	0.00	0.24	1.36	0.257	0.28	0.26	0.00	0.00	2.41
Bilobate *Setaria*-type	0.25	0.00	0.24	0.00	0.257	0.56	0.26	0.00	0.00	0.00
Bilobate scooped	0.49	0.00	0.24	1.09	0.514	0.00	0.53	0.00	0.00	0.48
Bilobate 1/2	0.00	0.00	0.00	0.00	0.000	0.00	0.00	0.00	0.00	0.00
Cross	0.74	0.00	0.00	1.09	0.257	0.00	0.26	0.00	2.99	0.00
Rondel	1.72	4.64	3.86	2.72	6.170	3.67	5.28	2.29	2.69	5.06
Stipa-type rondel	0.00	0.00	1.45	0.00	0.257	0.28	0.00	0.86	0.30	0.24
Saddle	0.00	0.00	0.00	0.27	0.514	0.00	0.53	0.00	0.00	0.48
Saddle collapsed	0.00	0.00	0.48	0.54	0.514	0.00	0.26	0.29	0.30	0.00
Saddle tall	0.25	0.00	0.00	0.54	0.257	0.00	0.26	0.00	0.00	0.48
Conical	1.47	0.58	2.41	0.54	1.028	1.41	1.32	2.86	1.79	0.72
Spheroid echinate	1.47	0.87	1.45	1.63	3.342	1.98	2.64	1.14	1.49	1.20
Spheroid ornate	2.94	1.45	2.41	1.90	2.571	2.54	1.32	0.00	0.90	1.20
Musa sp. Volcaniform	0.25	0.58	0.24	0.82	0.000	0.56	0.00	0.57	0.30	1.20
cf. *Musa* volcaniform	0.00	0.00	0.00	0.27	0.000	0.00	0.00	0.00	0.00	0.24
Single cell monocots	**35.05**	**26.96**	**41.45**	**36.68**	**38.05**	**34.75**	**33.77**	**42.86**	**31.05**	**34.70**
Spheroid psilate	11.27	6.38	5.06	6.52	6.427	6.78	6.60	2.86	8.36	7.47
Spheroid rugose	0.49	1.16	0.24	0.54	1.799	1.98	0.00	2.29	0.90	1.20
Tracheary	0.25	0.58	0.72	0.00	0.771	0.56	0.79	0.29	0.00	0.00
Sclereid	0.49	0.00	0.00	1.09	0.257	0.00	0.00	0.29	0.30	0.24
Reniform	0.25	0.00	0.00	0.27	0.000	0.00	0.00	0.00	0.60	0.24
Blocky	1.96	1.45	0.96	2.17	2.571	2.26	2.64	0.57	1.49	0.96
Faceted blocky facetate	0.74	1.16	1.45	1.09	1.799	0.85	2.37	0.57	2.99	1.93
Tabular psilate	2.45	3.48	0.96	1.90	2.057	4.52	2.64	2.00	2.69	1.93
Polygonal psilate	6.37	8.12	3.86	5.71	5.656	4.52	6.60	7.43	5.37	1.93
Scalloped	0.49	0.29	1.45	1.09	0.257	0.00	1.32	1.43	0.90	0.24
Brachiate (jigsaw puzzle)	0.49	0.58	0.24	0.54	0.000	0.00	0.53	0.29	1.19	0.96
cf. *Canarium*	0.00	0.00	0.00	0.27	0.000	0.00	0.00	0.00	0.00	0.00
Single cell dicots	**25.25**	**23.19**	**14.94**	**21.20**	**21.59**	**21.47**	**23.48**	**18.00**	**24.78**	**17.11**
Leaf/culm indet	15.69	19.42	14.46	12.23	14.139	17.80	15.57	20.00	14.03	15.66
Leaf/culm bilobes	0.00	0.00	0.00	0.54	0.000	0.00	0.00	0.00	0.00	0.00
Leaf/culm square cells	0.00	1.45	0.00	0.00	0.257	0.28	0.53	0.86	0.90	0.24
Leaf/culm with bulliforms	0.00	0.58	0.00	0.00	0.000	0.00	0.00	0.00	0.00	0.00
Leaf/culm long smooth	1.47	1.45	0.72	0.54	1.285	1.41	2.64	1.43	1.49	0.96
Leaf/culm Cyperaceae	0.98	0.00	1.93	1.36	1.285	0.85	1.06	0.86	0.30	1.69
Multi-brachiate panel	0.25	0.00	0.96	1.36	0.771	0.56	0.26	0.86	0.60	0.24
Indet husk	1.23	3.19	3.13	5.16	3.342	1.41	2.11	3.43	9.85	2.41
Indet *Poa* husk	0.49	0.58	0.48	0.00	0.000	1.69	2.37	0.57	0.30	0.24
cf. *Coix lacryma-jobi*	0.00	0.00	0.24	0.00	0.000	0.00	0.53	0.00	0.00	0.00
Polyhedral	1.23	1.16	1.20	1.90	1.542	2.26	2.11	0.29	0.90	2.89
Polyhedral hair base	0.25	0.00	0.24	0.27	0.257	0.28	0.00	0.29	0.00	0.24
Multispheroids	0.74	0.58	0.72	0.82	0.771	0.28	0.00	0.00	0.00	0.00
Other – indets.	**17.16**	**20.87**	**19.28**	**17.93**	**16.71**	**16.95**	**15.57**	**10.57**	**15.82**	**23.61**

Bold shows the total of single cell monocots, single cell dicots and other - indets.

Appendix D. Ta Prohm phytoliths

Archaeological feature	Sandy loam, changing soil from previous layers. Late 12th C AD	Primarily on western edge of unit. Soft sandy soil, with some charcoal pieces. Late 12th C AD	Primarily on western edge of unit. Soft sandy soil, with some charcoal pieces. Late 12th C AD	Fine pink sand, a lot of charcoal pieces. Late 12th C AD	Sandy clay with manganese. Few ceramics. Late 12th C AD	Soil sample from Trench 17 layer 4C Late 12th C AD
Sample number	16023 – Tr16 4b/4 g	17019 – Tr17 3D	17019 – Tr17 3B	17023 – Tr17 3b/3d	18014 – TR18 3b/4a	Tr17 4C
Elongate entire	12.69	10.55	12.83	9.48	12.87	11.04
Elongate sinuate	0.25	1.15	1.75	1.94	0.74	0.61

Elongate dendritic	0.00	0.46	0.29	0.65	0.25	0.31
Elongate dentate	0.75	0.23	0.29	1.29	0.50	1.53
Acute bulbous hair	7.96	4.36	4.96	8.41	4.70	5.21
Papillae	0.00	0.00	1.17	0.00	0.99	0.00
Bulliform	1.99	0.23	1.46	1.51	1.73	1.53
Bulliform flabellate	1.49	0.23	0.58	1.94	0.74	0.00
Oryza-type bulliform flabellate facetate	0.50	0.23	0.00	0.22	0.00	0.00
Bilobate	0.00	2.75	3.79	2.16	0.50	2.15
Bilobate *Setaria*-type	0.00	0.23	0.00	0.43	0.00	0.00
Bilobate scooped	0.00	0.46	1.75	1.29	0.00	0.31
Bilobate 1/2	0.00	0.69	0.00	0.00	0.00	0.31
Cross	0.00	0.69	0.87	0.00	0.00	0.92
Rondel	7.71	10.09	4.66	5.60	3.71	7.36
Stipa-type rondel	1.24	0.00	0.00	0.00	0.00	0.00
Saddle	0.75	0.46	0.87	0.86	0.25	0.00
Saddle collapsed	0.25	0.23	0.00	0.86	0.25	0.00
Saddle tall	0.75	1.61	1.75	0.00	0.00	0.00
Conical	0.75	2.29	0.58	0.65	0.74	3.37
Spheroid echinate	1.24	0.92	0.58	1.51	4.46	1.84
Spheroid ornate	1.24	0.23	0.87	1.51	2.97	3.07
Musa sp. Volcaniform	1.49	0.23	0.58	0.22	0.25	0.31
Single cell monocots	**41.04**	**38.30**	**39.65**	**40.52**	**35.64**	**39.88**
Spheroid psilate	6.22	5.27	5.26	5.17	10.16	5.22
Spheroid rugose	0.75	0.46	2.33	2.80	2.72	0.31
Nodular	4.23	2.98	1.75	0.00	3.22	3.68
Tracheary	0.00	0.69	0.58	0.86	0.74	0.31
Reniform	0.25	0.23	0.00	0.00	0.00	0.00
Blocky	1.99	1.61	0.00	0.22	0.50	1.23
Faceted blocky facetate	0.25	0.23	1.17	0.00	0.00	1.84
Sclereid	0.50	0.92	0.29	0.00	0.00	0.31
Tabular psilate	2.99	1.38	1.46	6.90	2.72	0.61
Polygonal psilate	6.97	4.59	6.12	4.96	5.45	7.98
Scalloped	0.25	0.23	0.58	0.43	0.99	0.00
Brachiate (jigsaw puzzle)	0.25	0.46	0.29	0.00	0.25	0.00
Single cell dicots	**24.38**	**18.81**	**19.84**	**21.34**	**26.75**	**21.48**
Leaf/culm indet	15.42	16.06	21.57	13.36	17.08	13.80
Leaf/culm square cells	0.75	0.00	0.58	0.22	0.74	0.92
Leaf/culm with bulliforms	0.00	0.46	0.00	0.22	0.00	0.00
Leaf/culm elongate entire	0.50	0.00	1.46	1.08	1.98	1.84
Leaf/culm cf. Cyperaceae	1.49	0.92	0.87	1.29	0.99	1.84
Leaf/culm cf. Panicoid	0.00	2.75	0.00	0.00	0.00	0.00
Multi-brachiate panel	0.25	0.00	0.29	0.43	0.25	0.92
Indet husk	3.73	0.23	1.75	1.08	6.93	5.52
Indet *Poa* husk	1.24	3.44	1.46	0.65	0.25	1.53
cf. *Oryza* husk	0.00	0.69	0.00	0.00	0.00	0.00
Panicum-type husk	0.25	0.00	0.00	0.00	0.00	0.00
Polyhedral	0.00	0.00	0.00	1.08	0.74	1.23
Polyhedral hair base	0.50	0.69	0.00	0.00	0.00	0.00
Arecaceae	0.00	0.92	0.00	0.00	0.00	0.00
Multispheroids	0.25	0.92	0.00	0.00	0.00	0.00
Other – indets.	**10.19**	**15.83**	**12.52**	**18.75**	**8.65**	**11.04**

Bold shows the total of single cell monocots, single cell dicots and other - indets

Appendix E. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ara.2020.100213.

References

Atal, C.K., Ojha, J.N., 1964. Studies on the genus *Piper*. Part IV. Long peppers of Indian commerce. Econ. Bot. 19 (2), 157–164.

Ball, T., Vrydaghs, L., Hauwe, I.V.D., Manwaring, J., Langhe, E.D., 2006. Differentiating banana phytoliths: wild and edible *Musa acuminata* and *Musa balbisiana*. J. Archaeol. Sci. 33, 1228–1236.

Barboni, D., Bremond, L., 2009. Phytoliths of East African grasses: an assessment of their environmental and taxonomic significance based on floristic data. Rev. Palaeobot. Palynol. 158 (1–2), 29–41.

Barthel, S., Isendahl, C., 2013. Urban gardens, agriculture, and water management: sources of resilience for long-term food security in cities. Ecol. Econ. 86, 224–234.

Bell, R.W., Seng, V., Schoknecht, N., Vance, W., Hin, S., 2005. Assessing land suitability for crop diversification in Cambodia. In: Proceedings of the Land Resource Assessment Forum on 23–26 September 2004 Held at CARDI, Cambodia.

Bhadri, K.M., 2007. Ta Prohm inscription of Jayavarman Vii, Ad 1186. In: Kapur, P.K., Sahai, S. (Eds.), Ta Prohm: A Glorious Era in Angkor Civlization. White Lotus Press, Bangkok, pp. 49–56.

Bouchaud, C., Yvanez, E., Wild, J.P., 2019. Tightening the thread from seed to cloth. New enquiries in the archaeology of Old World cotton. Revue d'Ethnoécologie 15 [online]. http://journals.openedition.org/ethnoecologie/4501.

Burkill, I.H., 1935. A Dictionary of the Economic Products of the Malay Peninsula. Published on behalf of the Governments of Malaysia and Singapore by the Ministry of Agriculture and Co-operatives, Kuala Lumpur.

Cameron, J., 2010. The archaeological textiles from Ban Don Ta Phet in broader perspective. In: Bellina, B., Bacus, E.A., Pryce, T.O., Christie, J.W. (Eds.), 50 Years of Archaeology in Southeast Asia: Essays in Honour of Ian Glover River Books, pp. 141–151 Bangkok.

Carter, A.K., 2015. Angkor Wat enclosure: June–July 2015. In: Internal Report on File with the APSARA Authority, Siem Reap.

Carter, A.K., Heng, P., Stark, M.T., Chhay, R., Evans, D.H., 2018. Urbanism and residential patterning in Angkor. J. Field Archaeol. 43 (6), 492–506.

Carter, A.K., Stark, M.T., Quintus, S., Zhuang, Y., Wang, H., Heng, P., Chhay, R., 2019. Temple occupation and the tempo of collapse at Angkor Wat, Cambodia. PNAS 116 (25), 12226–12231.

Castillo, C., 2013. The Archaeobotany of Khao Sam Kaeo and Phu Khao Thong: The Agriculture of Late Prehistoric Southern Thailand. Dissertation. UCL, Institute of Archaeology.

Castillo, C., Bellina, B., Fuller, D.Q., 2016. Rice, beans and trade crops on the early maritime silk route in Southeast Asia. Antiquity 90 (353), 1255–1269.

Castillo, C.C., 2019. Preservation bias: is rice overrepresented in the archaeological record? Archaeol. Anthropol. Sci. 11 (12), 6451–6471. https://doi.org/10.1007/s12520-018-0717-4.

Castillo, C.C., 2020. Food, craft and ritual: plants from the Angkorian world. In: Evans, D., Stark, M., Hendrickson, M. (Eds.), The Angkorian World.

Castillo, C.C., Polkinghorne, M., Vincent, B., Tan, B.-S., Fuller, D.Q., 2018a. Life goes on: archaeobotanical investigations of diet and ritual at Angkor Thom, Cambodia (fourteenth to fifteenth centuries CE). Holocene 28 (6), 930–944.

Castillo, C.C., Higham, C., Miller, K., Chang, N., Douka, K., Higham, T., Fuller, D.Q., 2018b. Social responses to climate change in iron age Northeast Thailand: new archaeobotanical evidence. Antiquity 92 (365), 1274–1291.

Chhem, R.K., 2005. Bhaisajyuaguru and tantric medicine in Jayavarman VII hospitals. Siksacakr 7, 8–18.

Chhem, R.K., Antelme, M.R., 2004. A Khmer medical text: the treatment of the four diseases manuscript. Siksācakr 33 (6), 33–42.

Coedès, G., 1906. La Stèle De Ta-Prohm. BEFEO 6 (1/2), 44–85.

Coedès, G., 1941. La Stèle De Práh Khan D'angkor. BEFEO 41, 255–302.

Czerniak-Drożdżowicz, M., 2018. The food of gods–«naivedya/nirmālya» in the Pāñcarātrika sources. Consonanze 3.

Dalby, A., 2002. Dangerous Tastes: The Story of Spices. British Museum, London.

de Waard, P.W.F., 1989. Piper nigrum. In: Westphal, E., Jansen, P.C.M. (Eds.), Plant Resources in South-East Asia. Pudoc, Wageningen, pp. 225–230.

Dy Phon, P., 2000. Vacanānukram rukkhajāti proe prās' knuṅ Prades Kambujā, Dictionnaire des plantes utilis.es au Cambodge, dictionary of plants used in Cambodia. Olympic, Phnom Penh.

Evans, D., Fletcher, R., 2015. The landscape of Angkor Wat redefined. Antiquity 89 (348), 1402–1419.

Evans, D., Fletcher, R., Pottier, C., Chevance, J.B., Soutif, D., Tan, B.S., Im, S., Ea, D., Tin, T., Kim, S., Cromarty, C., DeGreef, S., Hanus, K., Baty, P., Kuszinger, R., Shimoda, I., Boornazian, G., 2013. Uncovering archaeological landscapes at Angkor using lidar. PNAS 110 (31), 12595–12600.

Evans, D.H., 2016. Airborne laser scanning as a method for exploring long-term socio-ecological dynamics in Cambodia. J. Archaeol. Sci. 74, 164–175.

French, C., 2015. A Handbook of Geoarchaeological Approaches for Investigating Landscapes and Settlement Sites. Oxbow, Oxford.

Fuller, D.Q., 2008. The spread of textile production and textile crops in India beyond the Harappan zone: An aspect of the emergence of craft specialization and systematic trade. In: Osada, T., Uesugi, A. (Eds.), Linguistics, Archaeology and the Human Past Occasional Paper 3, Indus Project. Research Institute for Humanity and Nature, Kyoto, pp. 1–26.

Fuller, D.Q., Harvey, E.L., 2006. The archaeobotany of Indian pulses: identification, processing and evidence for cultivation. Environ. Archaeol. 11 (2), 219–246.

Fuller, D.Q., Korisettar, R., Venkatasubbaiah, P.C., Jones, M.K., 2004. Early plant domestications in southern India: some preliminary archaeobotanical results. Veg. Hist. Archaeob. 13, 115–129.

Fuller, D.Q., Castillo, C., Kingwell-Banham, E., Qin, L., Weisskopf, A., 2018. Charred pomelo peel, historical linguistics and other tree crops: approaches to framing the historical context of early Citrus cultivation in East, South and Southeast Asia. In: The History and Archaeology of the Citrus Fruit from the Far East to the Mediterranean: Introductions, Diversifications, Uses. Publications du Centre Jean Bérard, Naples, pp. 29–50.

Goodall, D., Jacques, C., 2014. Stèle inscrite d'Īśānavarman II à Vat Phu [English translation]. Aséanie 33, 405–454.

Green, G., 2000. Indic impetus? Innovations in textile usage in Angkorian period Cambodia. JESHO 43 (3), 277–313.

Green, G., 2003. Khmer costume and textile history. In: Traditional Textiles of Cambodia: Cultural Threads and Material Heritage. River Books, Bangkok, pp. 27–41.

Gutaker, R.M., Groen, S.C., Bellis, E.S., Choi, J.Y., Pires, I.S., Bocinsky, R.K., Slayton, E.R., Wilkins, O., Castillo, C.C., Negrao, S., Oliveira, M.M., Fuller, D.Q., d'Alpoim Guedes, J.A., Lasky, J.R., Purugganan, M.D., 2020. Genomic history and ecology of the geographic spread of rice. Nat. Plants 6, 492–502.

Hall, K.R., 1985. Maritime Trade and State Development in Early Southeast Asia. University of Hawaii Press, Honolulu.

Harris, P., 2007. Zhou Daguan: A Record of Cambodia, the Land and its People. Silkworm Books, Chiang Mai.

Heywood, V.H., Brummitt, R.K., Culham, A., Seberg, O., 2007. Flowering Plant Families of the World. Royal Botanic Gardens, Kew, Surrey.

Ho, A.Y., 1995. At the South-East Asian Table. Oxford University Press, USA.

Horrocks, M., Rechtman, R.B., 2009. Sweet potato (*Ipomoea batatas*) and banana (*Musa* sp.) microfossils in deposits from the Kona field system, Island of Hawaii. J. Archaeol. Sci. 36, 1115–1126.

Isendahl, C., 2012. Agro-urban landscapes: the example of Maya lowland cities. Antiquity 86 (334), 1112–1125.

Jacob, J., 1993. The ecology of Angkor: evidence from the Khmer inscriptions. In: Smyth, D.A. (Ed.), Cambodian Linguistics, Literature and History. School of Oriental and African Studies, London, pp. 280–298.

Jacob, J.M., 1978. The ecology of Angkor. Nat. Man South East Asia 109.

Katherine, H., 2004. Dressing Lord Jagannatha in silk: cloth, clothes, and status. J. Soc. Sci. 8 (2), 113–127. https://doi.org/10.1080/09718923.2004.11892408.

Kingwell-Banham, E., Harvey, E., Mohanty, R., Fuller, D., 2018. Archaeobotanical investigations into Golbai Sasan and Gopalpur, two neolithic-chalcolithic settlements of Odisha. Anc. Asia 9, 1–14.

Lustig, E., Lustig, T., 2013. New insights into "les Interminables listes nominatives d'esclaves" from numerical analyses of the personnel in Angkorian inscriptions. Aséanie 31, 55–83.

Lustig, E., Evans, D., Richards, N., 2007. Words across space and time: an analysis of lexical items in Khmer inscriptions, sixth–fourteenth centuries CE. J. Southeast Asian Stud. 38 (1), 1–26.

Lustig, T.L., Lustig, E.J., 2015. Following the non-money trail: reconciling some Angkorian temple accounts. JIPA 39, 26–37.

Macphail, R.I., Goldberg, P., 2018. Applied Soils and Micromorphology in Archaeology. Cambridge University Press, Cambridge.

Martin, M.A., 1983. Elements de medecine traditionnelle Khmere. Seksa Khmer 6, 135–170.

Maxwell, T.S., 2008. The stele inscription of Preah Khan, Angkor. UDAYA, J. Khmer Stud. 8, 1–114.

Mulholland, S.C., 1989. Phytolith shape frequencies in North Dakota grasses: a comparison to general patterns. J. Archaeol. Sci. 16, 489–511.

Nelson, S.C., Ploetz, R.C., Kepler, A.K., 2006. *Musa* species (banana and plantain). Species Profiles Pac. Island Agrofor. 15.

Nguyen, D.N.V., Nguyen, T., 2008. An Overview of the Use of Plants and Animals in Traditional Medicine Systems in Viet Nam. TRAFFIC Southeast Asia, Greater Mekong Programme, Hanoi.

Novello, A., Barboni, D., 2015. Grass inflorescence phytoliths of useful species and wild cereals from sub-Saharan Africa. J. Archaeol. Sci. 59, 10–22.

Pawar, V.A., Pawar, P.R., 2014. *Costus speciosus*: an important medicinal plant. IJSR 3 (7), 28–33.

Penny, D., Pottier, C., Kummu, M., Fletcher, R., Zoppi, U., Barbetti, M., Spmaneath, T., 2005. Hydrological history of the West Baray, Angkor, revealed through palynological analysis of sediments from the West Mebon. BEFEO 92, 497–521.

Penny, D., Pottier, C., Fletcher, R., Barbetti, M., Fink, D., Hua, Q., 2006. Vegetation and land-use at Angkor, Cambodia: a dated pollen sequence from the Bakong temple moat. Antiquity 80, 559–614.

Penny, D., Chevance, J.-B., Tang, D., De Greef, S., 2014. The environmental impact of Cambodia's ancient city of Mahendraparvata (Phnom Kulen). PLoS One 9 (1), e84252.

Penny, D., Hall, T., Evans, D., Polkinghorne, M., 2019. Geoarchaeological evidence from Angkor, Cambodia, reveals a gradual decline rather than a catastrophic 15th-century collapse. PNAS 116 (11), 4871–4876.

Piper, J.M., 1989. Fruits of South-East Asia: Facts and Folklore. Oxford University Press, Oxford.

Piperno, D.R., 2006. Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists. Rowman Altamira.

Pottier, C., Chhem, R.K., 2008. A la découverte d'un hôpital angkorien: résultats préliminaires d'une campagne archéologique au Prasat Tromoung. UDAYA, J. Khmer Stud. 9.

Pushpangadan, P., Kaur, J., Sharma, J., 1989. Plantain or edible banana (Musa x paradisica var–sapiemtum) some lesser known folk uses in India. Anc. Sci. Life 9 (1), 20.

Rosen, A.M., 1999. Phytolith analysis in near Eastern Archaeology. In: Pike, S., Gitin, S. (Eds.), The Practical Impact of Science on Aegean and Near Eastern Archaeology. Wiener Laboratory Publication 3. Archetype Press, London, pp. 86–92.

SCW, 2006. Atlas of Cambodia: National Poverty and Environment Maps. Save Cambodia's Wildlife, Phnom Penh.
Sharrock, P.D., 2009. Garuda, Vajrapāni and religious change in Jayavarman VII's Angkor. J. Southeast Asian Stud. 40 (1), 111–151.
Silva, F., Stevens, C.J., Weisskopf, A., Castillo, C., Murphy, C., Kingwell-Banham, E., Qin, L., Fuller, D.Q., 2018. A tale of two rice varieties: modelling the prehistoric dispersals of *japonica* and proto-*indica* rices. Holocene 28 (11), 1745–1758.
Smith, M.L., 2014. The archaeology of urban landscapes. Annu. Rev. Anthropol. 43 (1), 307–323.
Sonnemann, T.F., O'Reilly, D., Chhay, R., Flecther, R., Pottier, C., 2015. The buried 'towers' of Angkor Wat. Antiquity 89 (348), 1420–1438.
Stark, B.L., 2014. Urban gardens and parks in pre-modern states and empires. Camb. Archaeol. J. 24, 87–115.
Stark, M., 2015. Southeast Asian urbanism: from early city to classical state. In: Yoffee, N. (Ed.), The Cambridge World History. Cambridge University Press, Cambridge, pp. 74–93.
Stark, M.T., Evans, D., Chhay, R., Heng, P., Carter, A., 2015. Residential patterning at Angkor Wat. Antiquity 89 (348), 1439–1455.
Takachi, C.Y., Kondo, R., Tsutsuki, K., 2001. Opal phytoliths assemblage and its relation with plant biomass. 第四紀研究. Quat. Res. 40 (4), 337–344.
Thompson, A., 2004. Pilgrims to Angkor: a buddhist "Cosmopolis" in Southeast Asia? Bull. Stud. Dep. Archaeol. 3, 88–119.
Tseng, Y.C., Xia, N., Gilbert, M.G., 1999. Piperaceae. Flora China 4, 190–198.
Twiss, P.C., Suess, E., Smith, R.M., 1969. Morphological classification of grass phytoliths1. Soil Sci. Soc. Am. J. 33, 109–115.
Vaughan, J.G., 1970. The Structure and Utilization of Oil Seeds. Chapman & Hall, London.
Vrydaghs, L., Ball, T., Volkaert, H., Van den Houwe, I., Manwaring, J., Langhe, E.D., 2009. Differentiating the volcaniform phytoliths of bananas: *Musa acuminata*. Ethnobot. Res. Appl. 7, 165–177.

On-line resources

www.fao.org/cambodia/fao-in-cambodia/cambodia-at-a-glance/en/accessed17/07/18.