Archaeological and Anthropological Sciences (2019) 11:6473–6484
https://doi.org/10.1007/s12520-019-00794-8

ORIGINAL PAPER

The wet and the dry, the wild and the cultivated: subsistence and risk management in ancient Central Thailand

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Received: 7 July 2018 / Accepted: 22 January 2019 / Published online: 20 November 2019

Abstract

Increasing the productivity and yield of rice in Central Thailand has been a key focus of international and local government policy. Efforts have centered around producing a second winter season of irrigated rice. However, a series of droughts in the region have led to widespread crop failure. We carry out a re-evaluation of weather station and environmental data and combine this with new information from a key archeological site in Central Thailand, Phromthin Tai, whose occupation covers a long and critical period of Thai prehistory. Based on these data, we argue that farmers in the area employed an adaptive and resilient agricultural and wild-plant-food-based subsistence system that was adapted to the region's high variability in rainfall. This subsistence system bridged the divide between the wild and cultivated and between wet and dry farming. The temporal and spatial diversity inherent in this system makes it vulnerable to destruction by agricultural policies that focus singly on improving yields.

Keywords Rain-fed farming · Thailand · Yield gaps · Wild plant foods · Weeds

Introduction

Anthropologists have long commented that a neo-Malthusian (Malthus 1798) premise permeates agronomists and economists' justifications for increasing crop yield (Stone 2015): we may face disastrous consequences if we do not produce enough food. One of the only ways to achieve this goal, population control aside (Ehrlich 1968), lies in the promise of modern scientific agriculture. This concern has lead agronomic researchers and policy makers to identify measures to increase the production of grain crops and eliminate "yield gaps" (Licker et al. 2010; Mueller et al. 2012). Because of its high production and market value, maximizing rice's yield in Central Thailand (an area characterized by high variability in rainfall and frequent droughts) has been a focus of policy for both academic researchers and local governments, as well as NGOs and the World Bank (Kupkanchanakul 2000; Welch et al. 2010). This has primarily taken place through the promotion of a second season of irrigated, dry-season rice. However, despite the good intentions of these efforts, examples from around the world have shown that sometimes such policies have unintended consequences (Scott 1998).

Rice's role as a high yielding staple today, and the labor-intensive nature of the irrigation and water management systems that are hypothesized to have been necessary to support its growth has meant that it has also been a focus of archeobotanical research (Fuller and Qin 2009; King et al. 2014; following Wittfogel 1957).

In the ethnographic record, drought buffering systems of dry-land rain-fed farming and foods that bridge the divide between wild and cultivated play important roles in the subsistence systems employed by Central Thai farmers (Gajaseni and Gajaseni 1999). The archeological record has the potential to demonstrate

The full code used to produce the figures in this article is housed at: https://github.com/jguedes81/Lopburi/

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12520-019-00794-8) contains supplementary material, which is available to authorized users.

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how humans developed sustainable farming systems which were adapted to their local environmental over the longue duree.

Steven Weber argued that farming systems based on drought-resistant dryland crops such as millet formed long-term sustainable strategies for farmers in Central Thailand using data from sites dating to the early Neolithic to Iron Age (2400–200 BC), however, noted an increase in the importance of rice throughout the assemblage (Weber and Fuller 2008; Weber et al. 2010a). It is unclear what role rice played in the diet of the region following the Iron Age and to what degree irrigated forms of rice farming were employed.

Using archeobotanical data from a key site, Phromthin Tai (500 BC–900 AD) that spans the transition from prehistory to the historic period, we aimed to investigate what farming strategies were sustainable for farmers in Central Thailand over the millennia and a half of this site's occupation (from the Iron Age to the Dvaravati period). Did its inhabitants invest in irrigated rice, lowland wetland rice, or rather upland rain-fed varieties or dryland millet? We further employ data from the ethnographic record to question the categorization of several taxa as weeds and re-examine the record for past wild plant use in this region.

Rice production and water in Central Thailand

Rice production is closely linked to the control and availability of water. Rice lands in Thailand can be classified into several different types: irrigated, rain-fed lowland, deep water, and upland (Kupkanchanakul 2000). In the year 2000, over 80% of rice in Thailand was grown under rain-fed conditions as a wet-season crop that is planted with the start of the rainy season in May (Kupkanchanakul 2000). In recent years, policies aimed at increasing yields have promoted a second, irrigated, dry-season rice crop. This second crop is generally planted from November–February and harvested in March–June (Kupkanchanakul 2000). Eighty percent of the water supply that used to irrigate dry-season rice comes from highland reservoirs that have been largely developed by the Chao Phraya River Project (Shean 2015; Yoshito et al. 2004). These investments in irrigation infrastructure have allowed dry-season irrigated rice to gain ground in the past two decades at the expense of rain-fed, upland, and deep-water types of rice (Kupkanchanakul 2000). The introduction of non-photosensitive varieties of rice that can adapt to the shorter day lengths of winter has also allowed this transition to take place (Kittipong 1983). Efforts to improve rice's yield have also focused heavily on eliminating plants and other animal species that might compete with rice from the paddy through the application of herbicides and pesticides (e.g., Moody 1989; Tomita et al. 2003).

While the development of irrigation infrastructure has increased rice yields in Central Thailand through creating an additional production season, droughts and highly variable precipitation are still problematic for farmers. The volume of the Chao Phraya river depends largely on water stored by the Bhumibol and Sirikit dams and on total rainfall in the Northern region—sources that can be affected by changes in rainfall patterns. In addition, it is in this region that habitation and pressure on water resources are most dense, due in large part to the addition of an extra season of rice cultivation (Sethaputra et al. 2001). The Chao Phraya river basin has as a result faced some of the most serious water shortages in Thailand (Sethaputra et al. 2001). Between 2014 and 2016, drought plagued Central Thailand, reducing the water supplies in the Bhumibol and Sirikit Dams to their lowest levels since 1994. This prompted a large reduction in the lands cultivated in the dry season, ultimately reducing rice yields by roughly 30% across the country and requiring the Thai government to invest over 200 million USD to alleviate the drought in 2015 alone (Reuters 2015; Shean 2015).

The archeological and rich ethnographic records contain data on how rice farmers in early Central Thailand developed agricultural strategies designed to cope with fluctuating water availability.

Archeobotanical research in Asia has focused on documenting the spread and emergence of irrigated rice cultivation systems as the high labor requirements of this form of cultivation are argued to share close ties to the development of social complexity in the region (Boyd and Chang 2010; Higham 2014; Castillo et al. 2018). However, in other areas of the world, it is increasingly recognized that both contemporary and past farmers often achieved high returns through the use of diverse farming strategies, sometimes even within a single-family plot or region (Morrison 1994; Morrison 1996). Indeed, previous research has suggested that despite high levels of interdependence and social complexity, farming in Central Thailand may have been focused primarily on dryland farming (Mudar 1995; Weber and Fuller 2008; Weber et al. 2010a). Steven Weber (Weber et al. 2010b) argued that micro-regional models are necessary for understanding past agricultural practices and shifts within these practices over time. Ancient farmers, he argues, were uniquely attuned to the ecological constraints that surrounded them.

By combining archeobotanical data with an in-depth analysis of soil and weather station data, and the ethnographic record, we strive to create one such micro-regional models of how humans adapted their subsistence regimes to the ecological setting of Central Thailand.

Early farming in Central Thailand and the site of Phromthin Tai

Two of the key domesticates found in archeological sites across Southeast Asia, rice (*Oryza sativa*) and foxtail millet (*Setaria italica*), are presumed to have been introduced to the region from China where each of these crops was initially domesticated (Castillo 2011, 2017; Castillo et al. 2016b; Weber et al. 2010a). The earliest known evidence for cereal agriculture in Southeast Asia (c. 2400–2200 cal. BC) comes from sites excavated by the Thai archeometallurgy project that are located adjacent to Phromthin Tai and provide evidence for foxtail millet agriculture (Weber et al. 2010a). Rice appears to have been introduced to these sites during the Bronze Age (c. 700–500 BC) and increased in importance throughout the Iron Age (500 BC–200 AD) (Weber et al. 2010a).

In other regions of Thailand, such as the Mun River Valley, rice was cultivated under dryland conditions from about 1700 BC until a sharp fall in the strength of monsoon rains from about AD 200 stimulated what has been described as an agricultural revolution by prompting humans to invest in agricultural infrastructure (Higham 2014; Wohlfarth et al. 2016; Castillo 2017, 2018a). Moat/reservoirs and canals were then constructed, dryland weeds gave way to wet field indicators, iron plowshares and sickles were forged, and there was a remarkable rise in mortuary wealth for a rising social elite (Higham 2014; Wohlfarth et al. 2016; Castillo 2017, 2018a). It is unclear, however, what changes took place in agricultural production in Central Thailand during the Iron Age and early historic period (Table 1).

The Phromthin Tai site

Phromthin Tai (latitude: 100.621390°, longitude: 14.990556°) is located in the eastern Chao Phraya River Valley of Central Thailand in Lopburi province (Fig. 1). Archeological investigation began in 1991 when the Fine Arts Department of Thailand conducted a test excavation (Lertcharnrit 2006).

A total of 12 radiocarbon dates on archeobotanical material (primarily rice) from the site were carried out at the Oxford Radiocarbon Accelerator Unit (University of Oxford). We modeled the AMS dates in a Bayesian model (Supplementary information). Two key phases of occupation were present: phase 1.) the Iron Age (or between 200 BC and100 AD) and phase 2.) the Dvaravati period (400–550 AD) (Supplementary Fig. 1). A short gap of roughly 400 years is present between these two phases in our radiocarbon dates; however, this did not correspond to any evidence of abandonment or clear gap in stratigraphy in the archeological record. It is possible that this gap is due to sampling error and excavations taking place over a relatively small area of the site. Dvaravati occupations at the site were followed by a reoccupation during the Ayutthaya period from which we did not sample (Lertcharnrit 2006, 2014).

Phromthin Tai played an important role in regional systems of exchange. It was an important site for copper smelting, as evidenced by a 20-cm-thick layer of slag encountered in its Iron Age deposits (Lertcharnrit 2006). Copper ingots manufactured at Phromthin Tai have been demonstrated to be widely distributed across the region (Lertcharnrit 2006), and beads traded into the site show connections to Vietnam, India, and Northeast Thailand (Carter 2013:259; Lertcharnrit and Carter 2010: 68).

The cultivation strategies employed by the inhabitants of Phromthin Tai are unclear. The site's location suggests that its inhabitants may have employed different cultivation strategies to the neighboring and earlier Thai archeometallurgy project sites. Mudar's (1995) survey demonstrated that during the Neolithic, Bronze, and Iron Age, sites were located in areas of higher elevation terraces characterized by gleysols and vertisols: soils adapted to dryland farming but not suitable for different types of rice farming. Phromthin Tai is located on lower elevation terraces, today suitable for rice farming, which are composed of haplic fluvisols (naturally fertile alluvial silt) which are created from the flooding of the Chao Phraya River (Fig. 1) (Lertcharnrit 2014, 2006; Mudar 1995). Phromthin Tai is one of the few sites in the region with a Bronze Age occupation that maps onto these lower fluvisol terraces.

In her archeological survey of the Lam Maleng Valley, Mudar (1995) shows that the transition from the Iron Age to the Dvaravati period saw a reduction in site density and total area inhabited in the Lam Maleng Valley (Mudar 1995). Aside from a potential hiatus between AD 100 and 300 that might be due to sampling bias, Phromthin Tai seems to have weathered this transition and became the sixth largest site in the Lam Maleng Valley (Mudar 1993:203). The ability to cultivate rice in these lower alluvial terraces may explain why Phromthin Tai continued to be occupied during the Dvaravati period when many of the upland sites of the Lam Maleng valley were abandoned (Mudar 1993:188).

There is little clear evidence for infrastructure at the site that might be associated with irrigated rice during the Iron Age. During the Dvaravati period, however, some evidence for the ability to manage water is present in the form of moats at the site (Lertcharnrit 2006; Wanasin and Suphachanya 1981) (Fig. 2).

Stable isotope studies conducted on dental remains from the site, suggests that both rice and millet farming may have been important at the site. Liu (2018) found that the inhabitants of Phromthin Tai had

Table 1 Approximate timing of key phases discussed in the text

Period	Dates
Neolithic	2400–1300 BC
Bronze Age	c. 700–500 BC
Iron Age	500 BC–500 AD
Early Historic or Dvaravati period	500–900 AD

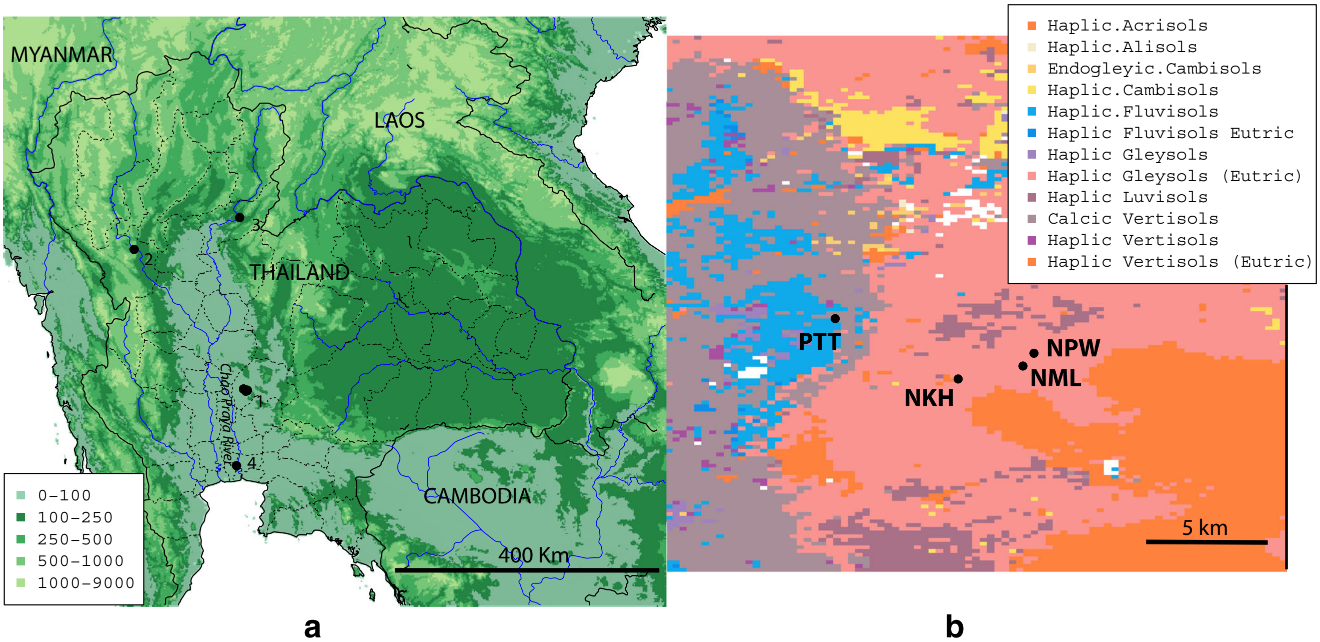


Fig. 1 **a** Location of the site in Thailand. Legend presents meters above sea level. 1.) Location of Phromthin Tai and the Thai archeometallurgy sites, 2.) Bhumibol Dam; 3.) Sirikit Dam; 4.) Bangkok. **b** Soil types surrounding Phromthin and Thai archeometallurgy sites. Raw data derived from Soilsgrid.org. (Code used to produce figure is presented in https://github.com/jguedes81/Lopburi/)

a mixed C_3–C_4 diet, with a slightly greater emphasis on C_3 foods, presumably rice.

In what follows, we employ an archeobotanical analysis to assess the role that different systems of farming played in the economy of Central Thailand during the Iron Age and Dvaravati period. Were the inhabitants of the site reliant on rice? If so, what type was this likely irrigated, lowland wet or rather upland rain-fed varieties? We also aim to assess the role played by other foods such as millet and wild plant foods.

Methods

A total of 38 archeobotanical soil samples were taken from Phromthin Tai-S4, a 6 × 6-m excavation unit (Lertcharnrit 2006), during the summer of 2015 by Sydney Hanson and were processed using simple bucket flotation (Hanson 2017). Samples were collected from both feature and general floor contexts of the excavation units. Features included but were not limited to industrial (slag) areas, soil within and around pottery vessels, charcoal concentrations, and animal

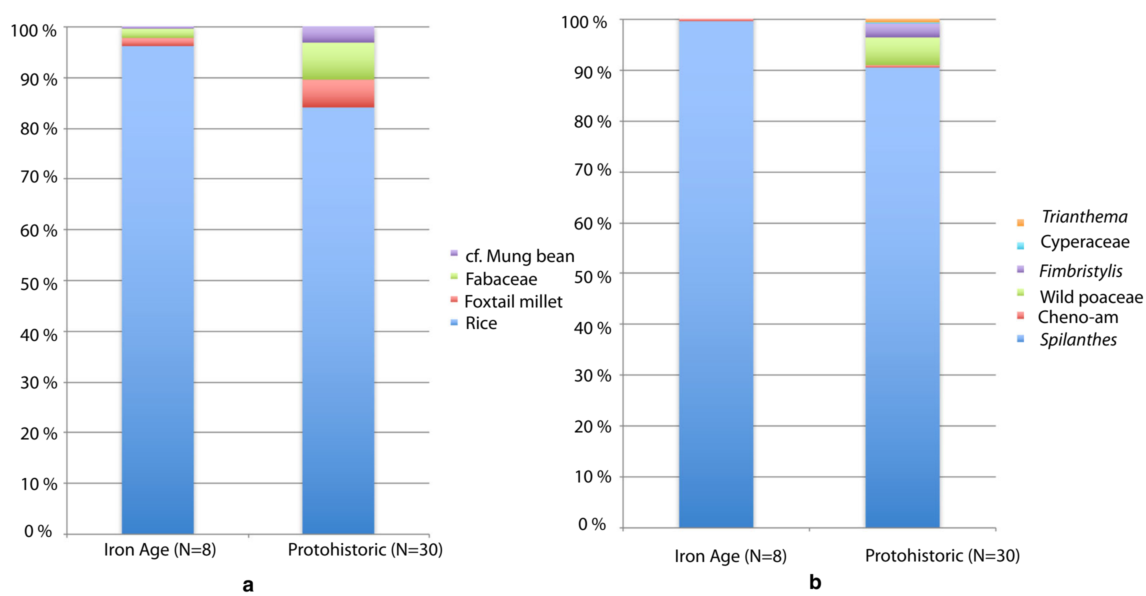


Fig. 2 Proportions of plant remains recovered at Phromthin Tai (based on counts). **a** Crops. **b** Wild plants/weeds. N = number of samples

bone concentrations. At Phromthin Tai, care was taken to avoid "feature bias" by sampling from general floor contexts, as well as from features. When possible, "companion samples," in the style of Lennstrom and Hastorf (1995), were taken from below samples for comparison purposes (d'Alpoim Guedes and Spengler 2014). Thirty samples were taken from Iron Age layers, and eight samples from the Dvaravati component of the site. We attempted to collect roughly 15-l samples; however, some ranged in size (Supplementary Table 1).

Half of the samples were processed using a 0.25-mm flotation cloth. The remainder were processed using slightly larger mosquito netting that had an aperture of 0.35 mm. This methodological error likely allowed some small seeds and other archeological plant material to pass through the fabric unrecovered. Once in the laboratory, samples were sieved into 2-mm, 1-mm, 0.5-mm, and 0.25-mm fractions that were examined separately under Olympus light microscopes using a variety of different magnifications at the Washington State University and University of California, San Diego. Reference was made to Jade d'Alpoim Guedes personal reference collection which consists of a large number of specimens from Asia as well to reference guides from the region.

Results

An analysis of the crop proportions at the site indicates that rice (*Oryza* sp.) was by far the most important crop (Fig. 2) followed by what is likely mung bean (*Vigna* sp.) and finally foxtail millet (*Setaria italica*).

An analysis of the numbers of rice spikelets indicates that the rice was not surprisingly domesticated (Supplementary Fig. 2). A large quantity of silicified rice husks were also present (Supplementary Table 2), suggesting that rice crop processing took place onsite.

It is presumed that early rice in Thailand moved into Southeast Asia from China and should belong to the species *Oryza sativa* subspecies *japonica* (Castillo 2011; Castillo et al. 2016b). A spread from South Asia may have involved *Oryza sativa* subspecies *indica*: a crop that was likely domesticated in the South Asian continent following hybridization with *japonica* species (Fuller et al. 2010). Given the date of Phromthin Tai as well as evidence for exchange with the South Asia, it is possible that either *japonica* or *indica* rice could have been cultivated at the site. Recent genetic data and morphometric data derived from the sites of Phu Khao Tong, Ban Non Wat, Noen U-Loke, and Khao Sam Kheo has shown that archeobotanical rice in Thailand dating to the Bronze and Iron Age largely conforms to an *O. japonica* cultivar (Castillo et al. 2016b). Presumably, *O. indica* rice was introduced to Thailand later, although some recent finds from Iron Age Ban Non Wat and Non Ban Jak suggest that small amounts of *O. indica* may have entered the assemblage (Castillo et al. 2018). Indeed, *indica* rice is the primary type of rice grown in Thailand today. While there is some overlap in morphometrics between *O. indica* and *O. japonica* varieties, *O. indica* generally fall into a length/width ratio of > 2.2 and *O. japonica* a ratio of < 2.0 (Castillo et al. 2016b).

The majority of grains at Phromthin Tai fall into the range of *O. japonica* rices in both the Iron Age and the Dvaravati period samples (Supplementary Fig. 3). The distribution of size ranges of rice at Phromthin Tai mirrors that found at other sites in Thailand which have been genetically demonstrated to belong to *O. japonica* populations (Castillo et al. 2016b). Only small numbers of grains may correspond to *O. indica* in both time periods. However, Castillo et al. (2016b) argue that an error margin of roughly 15% may exist in classifying grains, with an overlap between *O. indica* and *O. japonica* in the 2.0–2.4 range. Given the small numbers of these grains, it is likely that they correspond to *O. japonica*. While the inhabitants of the site were engaged in some types of exchange with South Asia, it appears that they did not readily adopt new cultivars of their staple food: rice. This is similar to patterns that have been noted at other sites in Southeast Asia where some Indian non-cereal cultivars were adopted but no change in rice variety took place (Castillo et al. 2016a).

A number of different specimens of bean (Fabaceae) were also identified. While the majority of these specimens were too poorly preserved for identification, several specimens are mung bean (*Vigna radiata*) (Fuller and Harvey 2006). The internal plumules on measured cotyledons have a plumule length: seed length ratio of 0.57–0.78 which corresponds to the published range for *V. radiata* (Fuller and Harvey 2006) (Fig. 3b). It is worth noting, however, that some overlap exists between mung bean (*V. radiata*) and the urad bean (*Vigna mungo*) (Fuller and Harvey 2006). One possible very poorly preserved specimen of *Vigna unguiculata* (cowpea) or *Macrotyloma uniflorum* (horse gram) was also found in the assemblage.

Beans have been demonstrated to shrink during charring, and the length and width of our specimen are similar to those presumed to be domesticated from sites in South Asia (Fuller and Harvey 2006). Although some wild populations of mung bean are found throughout Southeast Asia, Castillo and Fuller (2010) argue that it is unlikely to have been domesticated in this area. Mung bean may have been domesticated in two possible areas: the Eastern Himalayas or the Ghat mountains in India. They were a major crop in Neolithic South India (Fuller and Harvey 2006). This indicates that some trade in domesticates with South Asia had already taken place at Phromthin Tai by the Iron Age.

A single seed of another non-native domesticate, cotton (*Gossypium* sp.), was found in the Dvaravati layers of the site. This seed measures 5.3-mm long and 4.01-mm wide and is slightly flattened and comes to a small beak on the end. A

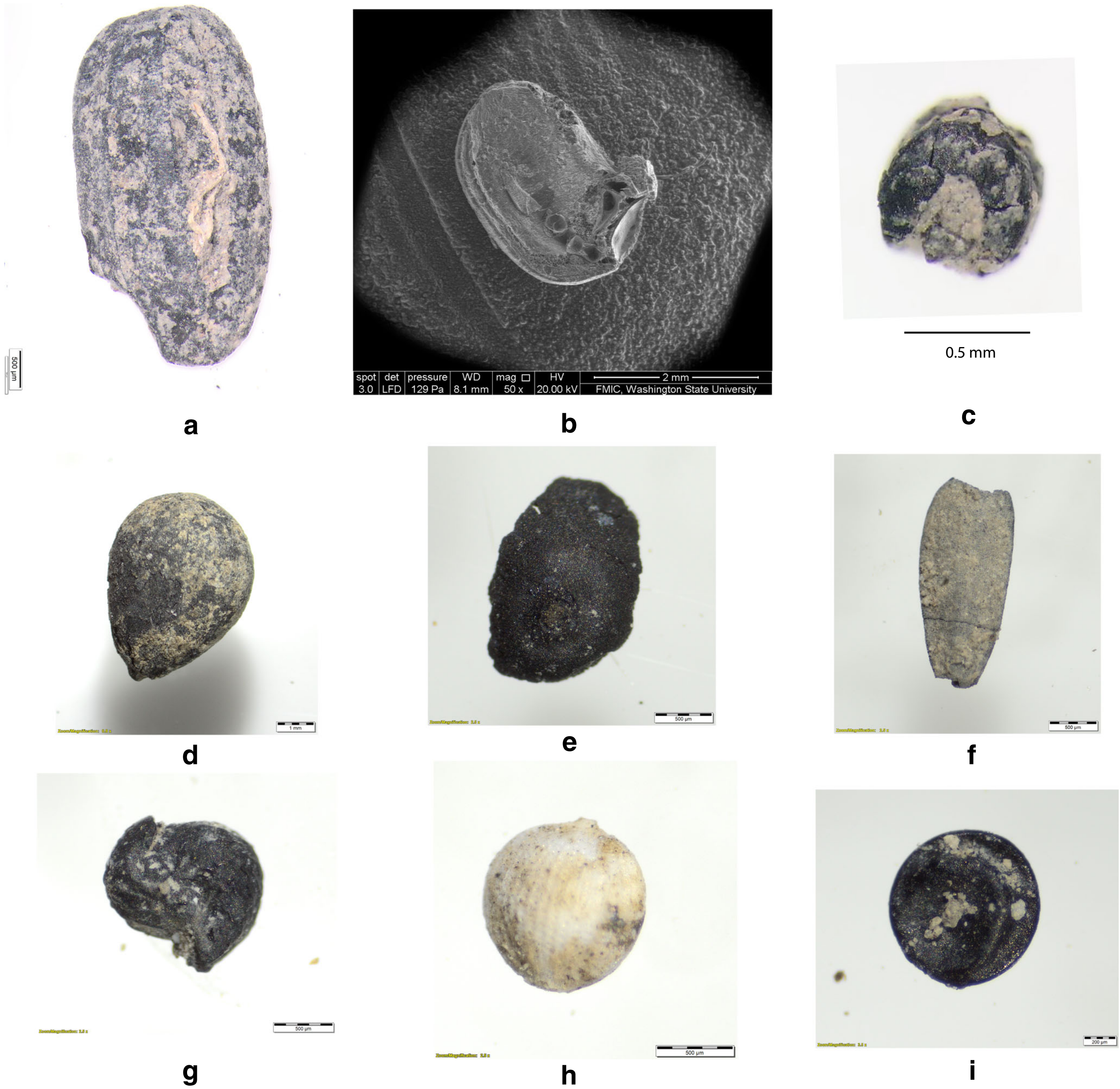


Fig. 3 **a** Rice (*Oryza sativa*) (sample #37); **b** cf. mung bean (*Vigna radiata*) (sample #24); **c** foxtail millet (*Setaria italica*) (sample #2); **d** cotton (*Gossypium* sp.) (sample #24); **e** cotton (*Gossypium* sp.) funicular "cap" (sample #10); **f** *Acmella paniculata* (sample #1); **g** *Trianthema* sp. (sample #1); **h** *Fimbristylis* sp. (sample #3); **i** *Chenopodium*/Amaranthaceae (sample #2)

visible raphe runs along the side of the specimen. We were also able to identify a fragment of the internal surface of the funicular cap whose vascular tissues presented a characteristic button-like structure (Bouchaud et al. 2011; Castillo et al. 2016a; Crowther et al. 2014; Crowther et al. 2016; Fig. 3d, e). Several scenarios could account for the presence of cotton seeds at the site. It is possible that it was cultivated elsewhere, and whole unprocessed bolls were shipped to the site for processing; however, it could also have been locally cultivated. In either case, seeds would have entered the archeological record as bolls were processed on site.

A number of plants traditionally classified as agricultural weeds have also been identified at the site. The majority of this assemblage is dominated by a member of the Asteraceae family: *Acmella paniculata* (3:F). Other weed seeds include *Fimbristylis* (3:H), another unidentified member of the Cyperaceae family, *Trianthema* sp. (3:G), a few poorly preserved specimens of *Chenopodium*/*Amaranth* (3:I), and a number of unidentified specimens of wild grass seeds (Poaceae).

Throughout time, our samples are heavily dominated by *Acmella paniculata*. *Acmella paniculata* (synonym *Spilanthes acmella*) has been argued to be a dryland weed found in both rain-fed and upland rice paddies (Castillo 2011; Soerjani et al. 1987). While *Fimbristylis* is a large genus, and members generally prefer upland and drier environments, some species such as *F. miliacea* prefer moister environments (Caton et al. 2004). *Trianthema* sp. and *Chenopodium/Amaranth* do not grow in paddy fields but rather upland/rain-fed environments (Moody 1989). Overall, the wild plant taxa present at the site suggest that they were derived largely from rain-fed or upland rice paddies and/or dryland environments (Caton et al. 2004).

Discussion

Our analysis shows that rice was clearly an important part of subsistence regimes at Phromthin Tai. Rice can be grown in both irrigated and rain-fed environments and both upland and lowland varieties of rice can be cultivated (Fuller et al. 2011; Kupkanchanakul 2000). Different varieties of rice will react differently to water stress or flooding. Rain-fed varieties are generally only grown in areas with minimal annual rainfall values of 800 mm (Jacquot and Courtois 1987) to 1000 mm (Yoshida 1981).

Between 1960 and 1990, the area around Phromthin Tai received a mean of 1100–1200 mm of annual rainfall, most of which fell between mid-May and mid-October (Mudar 1995) (Fig. 4). In the absence of irrigation infrastructure, rain-fed rice planting would have been limited to this period of the year.

Looking at historic variability in precipitation shows that farmers in Central Thailand have had to deal with highly variable rainfall. Data from the Lopburi station from 1951 to 2017 indicates that three major droughts where total rainfall was less than 500 mm have occurred in the instrumental record and an additional 14 droughts where annual precipitation was less than 1000 mm took place (Fig. 5). These droughts take place roughly 1 in every 4 years (Mudar 1995). Paleoclimate data indicates that monsoonal intensity has fluctuated in Thailand in the past broadly following the movement of the Intertropical Convergence Zone (ITCZ): an area currently located at 6° N. When temperatures in the Northern hemisphere are warmer, the ITCZ boundary moves north, bringing with it heavier monsoonal rain. Lake level records from the Khorat plateau demonstrate that driest conditions since the early Holocene peaked in the region between 3250 and 1250 cal. BC and continued until at least 350 AD before moving towards the wetter conditions that characterized the present day (Chawchai et al. 2013; Chawchai et al. 2015). While it is unclear exactly how much precipitation fluctuated in millimeters on annual basis in the past, this lake record suggests that summer precipitation (which is governed by the patterns of the East Asian monsoon) would have been lower than present between 3250 cal. BC and 350 AD: a period that corresponds to the establishment and development of farming in the region. Planting rain-fed rice may have been challenging during the period of the site occupation and promoted the inhabitants at Phromthin Tai to diversify the crops they grew. These droughts have implications for modern-day farming too as droughts deplete water reservoirs used for winter irrigated rice.

High variability in rainfall can also involve too much water. Phromthin Tai is located roughly 15 km from the Chao Phraya River, and the banks of this river have frequently flooded over in historic times during the monsoon season, often inundating fields and the immediate area surrounding Phromthin Tai (Gistda - Geo Informatics and Space Technology Development Agency [Thailand] 2017) (Supplementary Fig. 4). When minor floods occurred, rice farmers may have used water from the Chao Phraya river basin to complement precipitation by planting rice immediately after the flood. Indeed, these flooding events are important for returning fertility to the fields. However, a large-scale flood at the wrong time, such as the one that took place in 2011, can also quickly destroy rice crops (Supplementary Fig. 4). Early farmers at Phromthin Tai thus faced a delicate balance with regard to water resources, soil fertility, and rice cultivation. They may have employed a range of strategies to deal with these challenges including stream diversion, varying planting time, but also cultivating other crops to enhance their resilience.

Foxtail millet requires only between 250 and 400 mm annually (Saseendran et al. 2009; Seghatoleslami et al. 2008) and performs best in temperatures between 16° and 25 °C; winter temperatures in Central Thailand are generally at least this warm (Brink 2006; Cheng and Dong 2010; McMaster et al. 2011). It also has a short growing season of between 60 and 120 days depending on the variety (compared to rice which has a growing season length of 120–170 days), making it a useful crop that can be grown when other crops fail. Foxtail millet could have easily been grown during a winter rotation in this area; however, in years of drought, residents may have chosen to cultivate millet in the summer time. The inhabitants of the region may have practiced either a temporal or opportunistic diversification of food crop resources, one that enhanced their resilience to episodes of drought, by having a second season fall back crop: millets.

Home gardens that were employed in both wet and dry seasons could have played an important role for other economically important species such as legumes (Cruz-Garcia and Price 2011). Ethnographic studies have found that the diversity and density of wild plant foods whose growth was encouraged in home gardens increased during the dry season,

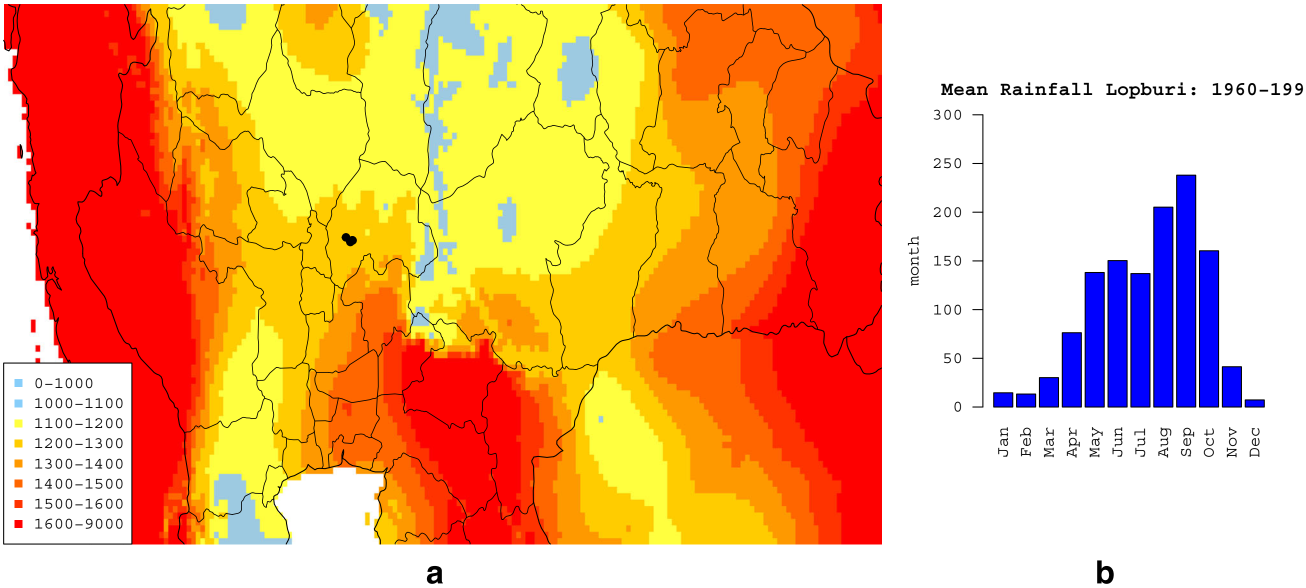


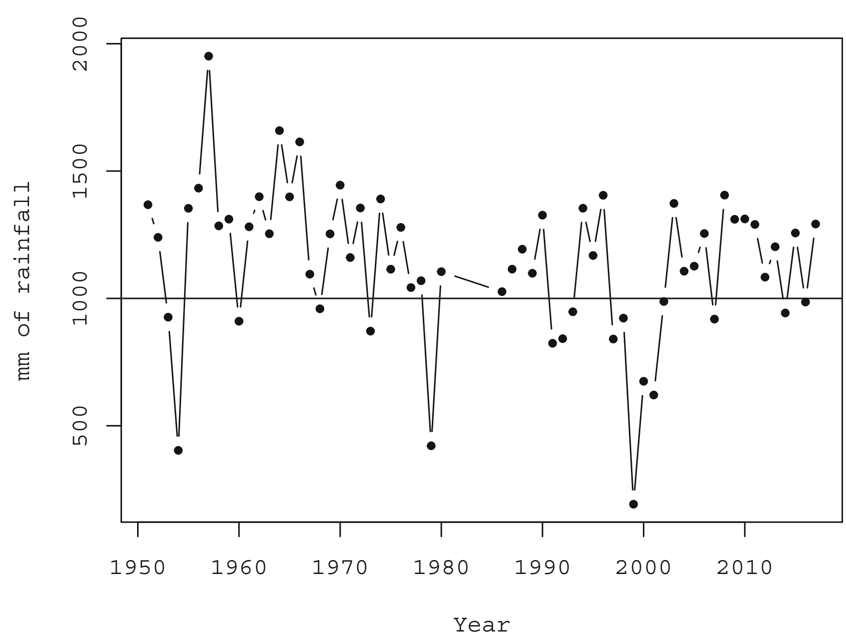
Fig. 4 Mean annual rainfall across Thailand. Areas in blue indicate regions that are not suitable for the cultivation of rain-fed rice. Data derived from Fick and Hijmans (2017). (Code used to produce figure is presented in https://github.com/jguedes81/Lopburi/)

making this an important time period for inhabitants to collect key resources beyond the rice field (Cruz-Garcia and Struik 2015).

In addition to these crops, fruit trees and wild resources may have been gathered in the savannas or forests that occupied higher elevations in the vicinity of the site. Rain-fed rice paddies have also been important sources of food in the ethnographic record of Thailand (Cruz-Garcia and Price 2011). Rice fields both in wet and dry seasons housed a wide range of commensal species that functioned as both food, medicine, and fodder and from an emic perspective are not classified as weeds but rather as useful economic species (Cruz-Garcia and Struik 2015). Our analysis reveals the presence of several species that have typically been classified as weeds such as Amaranthaceae, Chenopodiaceae, and *Acmella paniculata*.

In an ethnographic study of the Isaan region of Thailand, the leaves of *Amaranthus viridis* were reported to be a key wild food among informants (Cruz-Garcia and Struik 2015). The presence of *Chenopodium* and Amaranthaceae that showed a strong association with samples containing millet indicates that while these plants may have functioned as commensal "weeds" with millet, they also likely served an additional function as food, as they have been demonstrated to have done elsewhere in Asia (d'Alpoim Guedes and Butler

Fig. 5 Annual precipitation data from the Lopburi station. Data derived from the Global Historical Climatological Network. Data range from 1951 to 1990 (Menne et al. 2012). (Code used to produce figure is presented in https://github.com/jguedes81/Lopburi/)



2014; Yang and Liu 2009; Zhao and Chen 2011). *Acmella* greens commonly are sold as vegetables in Thailand, where it is known as *phak khraat* in Thai (Castillo 2018a; Jacquat 1990:91–92, 80). The seeds of this plant have been reported to be used for medicinal purposes in the ethnographic literature in Taiwan, Bangladesh, Assam, and throughout South Asia (Biswas et al. 2010; Chung et al. 2008; Hossan et al. 2010; Sharma and Pegu 2011). While this plant may have indeed accompanied rice as a commensal weed, we argue that its present economic importance as a vegetable was likely not lost on the inhabitants of ancient Thailand and indeed its ubiquitous presence at this and other Thai sites may be due to farmers encouraging its growth alongside rice as an important wild food resource. Even the stems of plants such as *Fimbristylis* have been demonstrated to be ethnographically important for making mats (Caton et al. 2004).

Growing cash crops like cotton could have been another way that inhabitants of the site diversified their holdings. Investing in the production of trade items like textiles, metal, and beads could have allowed them to obtain both crops and goods through networks of exchange (Castillo et al. 2016a, b; Fuller 2008). Large numbers of spindle whorls uncovered at the site suggest that some form of textile production may have been an important industry at the site.

Conclusion

The high number of *O. japonica* rice finds accompanied by small amounts of foxtail millet at Phromthin Tai shows that farming systems were reliant on a mixed type of cultivation system. As has been argued to be the case in Southwest China, these two crops functioned as a package that allowed farmers to adapt to environments both low in water and in other instances, high in altitude, and that characterized areas such as southwest China (d'Alpoim Guedes 2011; d'Alpoim Guedes and Butler 2014; Weber et al. 2010a, b). Foxtail millet may have functioned as either a dry season or a catch crop during years of drought when cultivating rice was difficult. Another study in this special issue shows that rice grains tend to preserve better in archeological sites than millet, and as a result, lower quantities of millet in the archeobotanical assemblage may not reflect its actual usage patterns (Castillo 2018b, this issue).

The presence of *Vigna radiata* and cotton (*Gossypium* sp.) indicate that Phromthin Tai was likely part of a network of trade that extended as far as South Asia (Castillo et al. 2016a:1257). Despite exchange in these two domesticates, farmers at Phromthin Tai conservatively retained their own staple crops and may not yet have adopted *O. indica* varieties of rice: something that genetic analysis of this rice must investigate.

Farming patterns at Phromthin Tai were thus substantially different from those documented in the Mun River valley where water conservation and irrigation involved moat/reservoirs, canals, proliferation of wetland weed seeds, and the forging of iron plowshares. Moreover, no millet has been identified in any of the Mun sites (Castillo et al. 2018). A lack of moats at Phromthin Tai during the Iron Age suggests that if irrigation systems were employed at the site, they were smaller in scale and may have only involved stream diversion and opportunistically employing overbank flooding. Even after moats appeared at the site during the Dvaravati period, the continuation of dryland "weed" species in the archeobotanical record suggests that rain-fed cultivation of rice (potentially aided or abetted by flooding) was a resilient strategy that lasted several millennia at Phromthin Tai. Regional diversity in farming was a major feature of the period from the Iron Age to the formation of early states across Thailand with Central Thailand showing different types of practice to the Mun River Valley.

Cultivating rain-fed rice combined with other catch crops has historically been a crucial strategy to farmers in Central Thailand. The recent push to a winter rotation of irrigated rice has been shown to have a low resilience to multi-year episodes of drought as water reservoirs can be easily depleted. In addition, practices which aim to expand the spatial dimensions of rice fields may impact the area given to home gardens in which biodiverse wild and cultivated plants that provide crucial food security for Thai farmers can be found (Gajaseni and Gajaseni 1999). Higher yield in a key grain crop with international market values has largely driven the push to cultivate a new winter rice rotation. However, this may ignore the long-term adaptive strategies of farmers in Central Thailand who employed a variety of crops with variable water requirements and legumes, allowing them to adapt to the high variability of the environment that they occupied.

As international rhetoric aims to increase rice production by more intensive farming methods and double cropping, the richness of the other crops cultivated during the dry season should not be forgotten. The archeological and ethnographic records demonstrate that this served as a key time for cultivating drought-resistant crops such as millets, for vegetable and fruit production, and for the gathering of wild plant foods. Ethnographic reports from Northeast Thailand attest that over half the total food consumed in villages can come from wild resources (Cruz-Garcia and Price 2011). Many wild plant resources come from fruit trees and terrestrial herbs that grow in home gardens, forest patches, upland fields, and rice paddies (Coomklang et al. 2000; Cruz-Garcia and Price 2011; Gajaseni and Gajaseni 1999; Rigg 1993; Somnasang et al. 1998; Somnasang and Moreno-Black 2000). In addition to plants, wild foods that occupy paddies during the rainy season can include lizards, crabs, frogs, insects, shellfish, and fish.

However, contemporary farming practices aimed at improving yield encourage farmers to eliminate wild "weeds" or "pests" from their fields which compete with rice. These strategies may have unintended consequences and may eliminate species that have played central roles in the rich systems of Thai subsistence and cuisine throughout the centuries (Bambaradeniya and Amerasinghe 2003; Cruz-Garcia et al. 2016; Price 2000). Thai responders in fact prefer wild to cultivated food because of the ease involved in its procurement, its reliability compared to cultivated crops, and its reportedly higher nutrition (Rigg 1993; Somnasang and Moreno-Black 2000). Both the ethnographic data and the deep time record of subsistence at Phromthin Tai suggest that we should consider these plant foods from a different perspective: one that acknowledges the diversity in plant foods as well as seasonal practices employed by Thai farmers. Ironically, the well-intentioned focus on rice for food security may decrease both resilience and biodiversity of resources consumed and sold by farmers in Central Thailand (Price 2000).

What is and is not considered food is above all cultural, and as Thai farmers are asked to employ practices that render their rice fields "legible" and high yielding (Scott 1998), critical elements of the diet may be eliminated as weeds or nuisance, ultimately decreasing farmer resilience. It is indeed these foods that bridge the conceptual divide between wild and domesticated that often play a crucial role in maintaining food security (Logan 2016; Morell-Hart 2012), particularly in areas such as Central Thailand with long-term legacies of drought. Likewise, practices aimed at adapting to high variability in water such as intercropping with millets may be seen as impediments to closing "yield gaps." The deep time history of these practices in Central Thailand provides lessons for how to achieve resilient agricultural systems not just for the decades but for the millennia of Thai farming represented by the archeological record.

Acknowledgements Thanik Lertcharnrit is grateful to the support from the Thailand-United States Educational Foundation and the Fulbright foundation which supported a research visit to Washington State University. We thank the staff of the Oxford Radiocarbon Accelerator Unit at the University of Oxford for their careful laboratory work. We are grateful to the comments from two anonymous reviewers whose detailed comments helped improve this manuscript.

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