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Human adaptation to mid- to late-Holocene climate change in Northeast Thailand

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Abstract

This article integrates palaeoenvironmental and archaeological sequences covering the mid- to late-Holocene in Northeast Thailand. The former reveal the fluctuating intensity of the Asian summer monsoon, leading to periods of higher moisture availability with intervals of relative aridity. The latter are founded on a series of new radiocarbon determinations that provide a basic chronological framework, from the initial Neolithic settlements by rice farmers (c. 3700 cal. BP) to the end of the prehistoric Iron Age around 1300 cal. BP. By dovetailing the two, we find that periods of relative aridity occurred during the later Iron Age as an agricultural revolution witnessed water control measures, plough and irrigated rice cultivation and a marked rise in social elites. The correlation between climatic and cultural changes is found to continue into the period of the Angkorian state. Rather than cause a decline and/or abandonment of late Iron Age settlements, we find that the environmental stress caused by a weaker summer monsoon was met by a strong social response and by adaptations that generated a transition into early socially hierarchic polities.

Keywords

Bronze Age, Iron Age, multi-proxy lake sediment studies, Neolithic, Northeast Thailand, palaeo-monsoon, social adaptation

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Introduction

The monsoon climate of Northeast Thailand is characterised by a period of intense rains from May to September, followed by months of virtually no precipitation (October–April), when the northeast or winter monsoon dominates. Most of the summer rainfall derives from advection of moisture from the Indian Ocean, although tropical cyclones originating in the Western North Pacific Ocean and in the South China Sea can bring additional moisture to the region (Chawchai et al., 2013).

Rice has a long history in Southeast Asia, being introduced by initial Neolithic settlers migrating into Northeast Thailand around 3700 cal. BP (c. 1750 cal. BC; Higham et al., 2015). Rice, which is an important staple, can be cultivated in many different ways, from fields cut from the forest and sustained by natural rainfall to multiple cropping in wet rice fields fed by irrigation. Rice cultivation is thus heavily dependent on rainfall and water availability. The inhabitants of Northeast Thailand rely on the rainy season for a single crop of rice, but this can be doubled through water conservation and irrigation.

Drought or flooding due to much drier or much wetter than normal conditions is a recurrent feature in monsoonal Asia and has been related to El Niño and La Niña events, respectively (e.g. Singhrattna et al., 2012). The effects that a much weaker or a much stronger summer monsoon has, and has had, on agricultural societies in Asia have been widely discussed, both in present-day and historical contexts (e.g. Buckley et al., 2014; Cook et al., 2010; Lieberman and Buckley, 2012; Miyan, 2015). On a broader canvas, it has been argued that drought generates social stress. Notable examples include the collapse of the Maya in Central America (Haug et al., 2002; Hodell et al., 1995; Kennett et al., 2012; Medina-Elizade and Rohling, 2012), the fall and rise of kingdoms in Africa (see, for example, Hannaford, 2014 for an extensive literature review), the abandonment of Angkor in Cambodia (Buckley et al., 2010; Cook et al., 2010; Lieberman and Buckley, 2012) and Chinese dynastic instability (Buckley et al., 2014; Cook et al., 2010; Yancheva et al., 2007; Zhang et al., 2008). All these may have been triggered by prolonged intervals of severe drought and/or strongly fluctuating rainfall.

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An alternative view to the 'drought theory', which often assumes a direct link between climate, environmental response and human inability to adapt, emphasises the prominent role that societal and political factors may have played (Buckley et al., 2014; Lieberman and Buckley, 2012). An elegant example, which combines a multi- and interdisciplinary approach, to address questions of adaptation and resilience to climate change, is the review by Dugmore et al. (2012), who discussed the fate of the Norse in Greenland. The collapse of this society has often been attributed to its inability to cope with the marked temperature decline at the start of the 'Little Ice Age'. Dugmore et al. (2012) however argue that the society declined because of its

> inability to anticipate an unknowable future, an inability to broaden their traditional ecological knowledge base, and a case of being too specialized, too small, and too isolated to be able to capitalize on and compete in the new protoworld system extending into the North Atlantic in the early 15th century. (p. 3658)

Studies addressing the link between historic societies and past climate change are supported by precise, sub-decadal palaeoclimate records derived from tree rings and speleothems, and also by written records (e.g. Buckley et al., 2014; Cook et al., 2010). Those linking prehistoric societies and past climatic and environmental changes on longer time scales, however, involve chronologically less precise palaeoclimatic and archaeological information. Yet we know, based on palaeoclimate records for monsoonal Asia, that the strength of the summer monsoon has varied on decadal to centennial time scales throughout the Holocene (e.g. Chawchai et al., 2013; Wang et al., 2001; Zhang et al., 2008). Shifts in summer monsoon intensity can thus be expected to have had an impact also on prehistoric societies.

This paper has been made possible through a new chronological framework for the prehistoric cultural sequences in Northeast Thailand covering a period of about 2300 years (Higham, 2014; Higham et al., 2011b, 2015) and multi-proxy lake sediment studies on the Khorat Plateau that allow reconstructing Holocene summer monsoon variability (Figure 1a–c; Chawchai et al., 2013, 2015a, 2015b). Together these studies permit, for the first time, an exploration of cultural adaptations in Northeast Thailand in the context of a precise chronological framework and new evidence for past climatic changes.

The palaeoenvironmental records from Lakes Kumphawapi and Pa Kho (Figure 1c) reveal marked fluctuations in moisture availability throughout the past 10,000 years (Chawchai et al., 2015a, 2015b) and provide a background scenario to address the following questions: To what extent did the social changes that took place coincide with climatic variability? Did the prehistoric inhabitants display resilience and adaptability, or stasis and decline?

Regional moisture/environmental history: The records of Lakes Kumphawapi and Pa Kho

Lake Kumphawapi

Lake Kumphawapi (17°11′N, 103°02′E; 166 m above mean sea level; Figure 1c), Thailand's largest natural freshwater lake, contains a Holocene sedimentary record of environmental changes (Chawchai et al., 2013, 2015b; Kealhofer, 1996; Kealhofer and Penny, 1998; Penny, 1998; Penny et al., 1996; Wohlfarth et al., 2012). Initial studies had focused on the vegetation development based on multiple sediment cores from different parts of the lake (Kealhofer, 1996; Kealhofer and Penny, 1998; Penny, 1998; Penny et al., 1996). These formed the basis for further multi-sediment and multi-proxy investigations of sediment sequences CP3A, CP3B and CP4, all of which are located in the central and southern parts of the basin (Chawchai et al., 2013, 2015b; Wohlfarth et al., 2012; Figure 1c).

Radiocarbon chronologies (based on ^{14}C dates on terrestrial plant remains) and inorganic and organic bulk geochemistry, combined with diatom stratigraphy (CP3A), biogenic silica analysis and hydrogen isotope (δD) measurements on lipid biomarkers (CP4), and plant macrofossil and charcoal analyses (CP3B), now allow reconstructing lake status changes in time and space (Chawchai et al., 2013, 2015b; Wohlfarth et al., 2012). Age–depth models for the three sequences were constructed using a Bayesian statistics–based routine (Chawchai et al., 2015b; Wohlfarth et al., 2012). This latter approach highlighted the presence of multiple hiatuses of various lengths (Figure 2) and also allows quantifying the statistical age error for each sequence at each given data point. The start/end of the hiatuses is most distinct in CP4 and CP3B, where ^{14}C ages abruptly shift from older to much younger ages within a few centimetres of sediment (Chawchai et al., 2015b). In CP3A, however, these shifts are less pronounced and the partly controversial ^{14}C dates (Wohlfarth et al., 2012) could allow for different scenarios: continuous deposition and low sedimentation rates, post-depositional disturbance of the highly organic sediments or two shorter hiatuses. Using supporting evidence, such as sediment composition and high amounts of charcoal and soil particles, Wohlfarth et al. (2012) argued that a hiatus could best explain these problematic layers. In the recently published update for Lake Kumphawapi, Chawchai et al. (2015b) suggested that the hiatuses observed in the three sediment sequences extend between 6500 and 2700 cal. BP (4550–750 cal. BC) and between 2300 and 1400 cal. BP (350 cal. BC and cal. AD 550) in core CP4 from the southernmost part of the lake, and between 6200 and 3800 cal. BP (4250–1850 cal. BC), between 5400 and 4000 cal. BP (3450–2050 cal. BC) and between 2400 and 1800 cal. BP (c. cal. AD 450–150) in sediment sequences CP3A and CP3B from the southeast part of the lake (Figure 2). Below the major hiatus, modelled maximum age errors are in the range of ±50–250 years for CP4 and CP3B, but up to ±600 years for CP3A. Post-hiatus ages have similar modelled maximum errors of ±50–250 (CP4, CP3B) and ±150–300 years (CP3A), but the chronology for the past 2000 years is poorly constrained when compared with Lake Pa Kho (Chawchai et al., 2015a).

Although more work will have to be carried out to fully understand the depositional history of Lake Kumphawapi in time and space, the available multi-sediment and multi-proxy data sets (Chawchai et al., 2015b) now allow refining past lake status changes and their link to regional moisture availability (Figure 2). The change in lake status (lake level lowering and transgressive wetland expansion) around 7000–6700 cal. BP was earlier explained as evidence for gradually drier conditions (Chawchai et al., 2013; Wohlfarth et al., 2012). However, hydrogen isotopes (δD) on long-chain *n*-alkanes ($C_{n\text{-}29,31}$), which are produced by leaf waxes of terrestrial plants, now show that regionally wettest conditions occurred between 7000 and 6600 cal. BP (5050–4650 cal. BC; Figure 2). Wetter conditions led to enhanced biomass production, which in turn contributed to and accelerated lake infilling, causing an apparent lake level lowering (Chawchai et al., 2015b).

Unfortunately, the long hiatus in CP4 prevents a reconstruction of regional moisture history based on δD measurements (Figure 2). However, lithological and geochemical evidences led Chawchai et al. (2013, 2015b) to suggest that the hiatuses, which coincide with Kumphawapi's wetland/peatland phase, reflect alternating intervals of drier and wetter conditions. Especially dry conditions seem to have prevailed between 5400 and 4000 cal. BP (3450–2050 cal. BC), when all three sediment sequences display

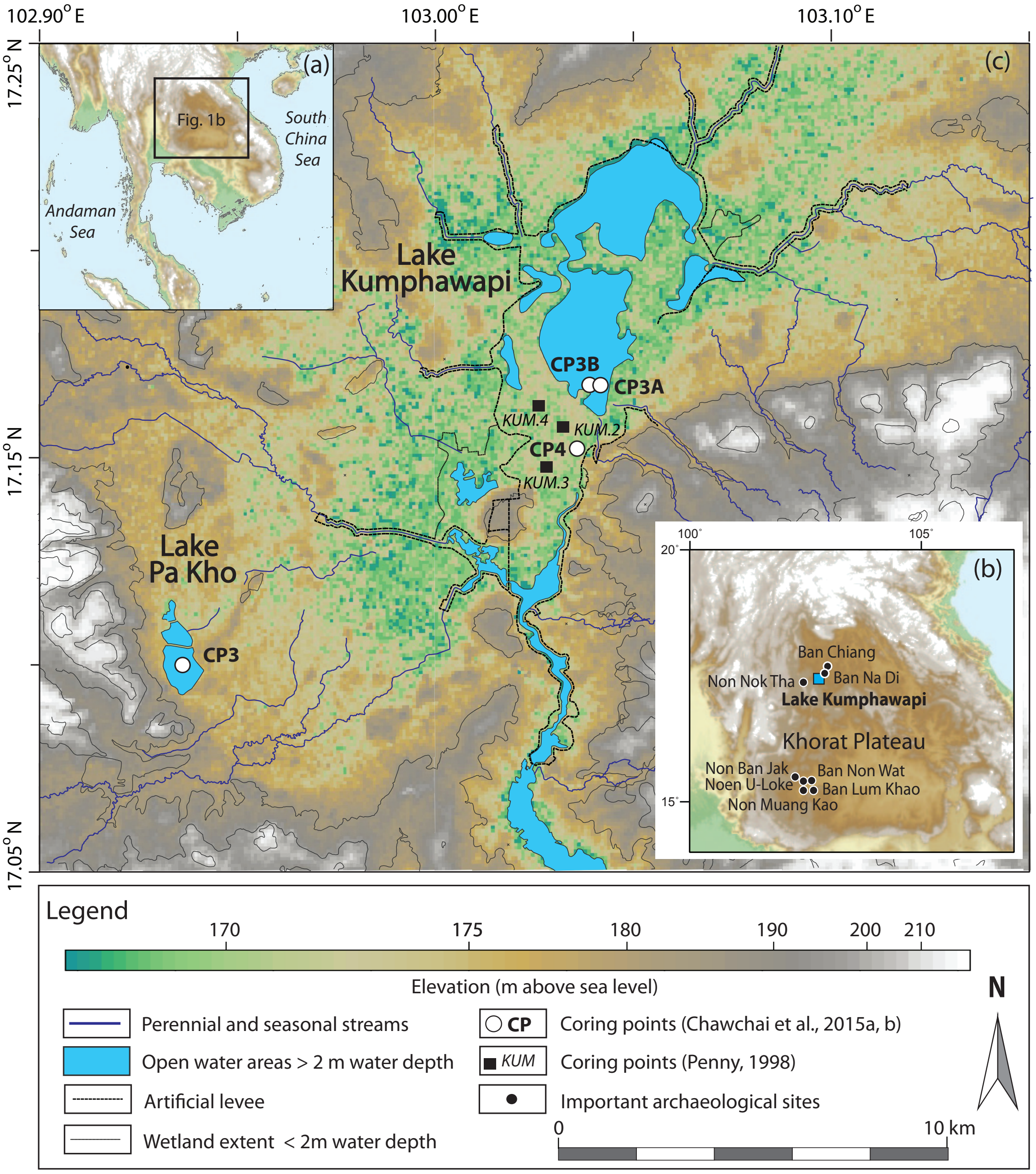

Figure 1. (a) Southeast Asia and the location of the study region on the Khorat Plateau of northeastern Thailand; (b) important archaeological sites on the Khorat Plateau mentioned in the text; (c) topography of Lakes Pa Kho and Kumphawapi and location of the lake sediment/peat sequences discussed in the text. See Wohlfarth et al. (2012) and Chawchai et al. (2013, 2015b) for details on sequences CP3A, CP3B and CP4; Kealhofer (1996), Kealhofer and Penny (1998), Penny et al. (1996) and Penny (1998) for sequences KUM.2, KUM.3 and KUM.4 from Lake Kumphawapi; and Chawchai et al. (2015a) for details on CP3 from Lake Pa Kho.

a hiatus. Since the hiatus in CP3A and CP3B ends around 4000–3800 cal. BP (2050–1850 cal. BC), but only around 2700 cal. BP (750 cal. BC) in CP4, one can assume that deeper parts of the basin became water filled, while more marginal areas remained dry. The hydrogen isotope data set for CP4 shows that moisture availability was still low around 2700–2300 cal. BP (750–350 cal. BC); the distinct increase in macroscopic charcoal between approximately 3500 and 2100 cal. BP (c. 1550–150 cal. BC) in CP3B and CP4 could thus derive from burning of the peat surface during extreme drought conditions (Figure 2). However, since we have indications for human presence in the region, at least after 3000 cal. BP (1050 cal. BC), the increase in charcoal could also point to human activities close to the lake (Figures 3 and 4).

The upper hiatus between 2400 and 1400 cal. BP (450 cal. BC–cal. AD 550) in CP3A and CP4 may be explained by erosion and reworking of the underlying layers during the rise in lake level that started around 1800 cal. BP (c. cal. AD 150; Chawchai et al., 2015b). Higher lake levels would suggest an overall increase in moisture availability, while the hydrogen isotope data set points to only slight changes and to overall drier conditions during the past 1400 years (Chawchai et al., 2015b; Figure 2). High amounts of macroscopic charcoal between around 1600 and 1000 cal. BP (cal. AD 350–950) and the marked increase in primary productivity in the lake between 1000 and 600 cal. BP (cal. AD 950–1350) in CP3A and CP4 could both point to increased human impact (Chawchai et al., 2015b; Wohlfarth et al., 2012). The timing of hydroclimatic changes during the past 2000 years is, however, not well constrained in the sediments of Lake Kumphawapi. Instead, the high-resolution record from nearby Lake Pa Kho (Figure 1c) provides a detailed picture of regional moisture availability for the past 2100 years (Chawchai et al., 2015a).

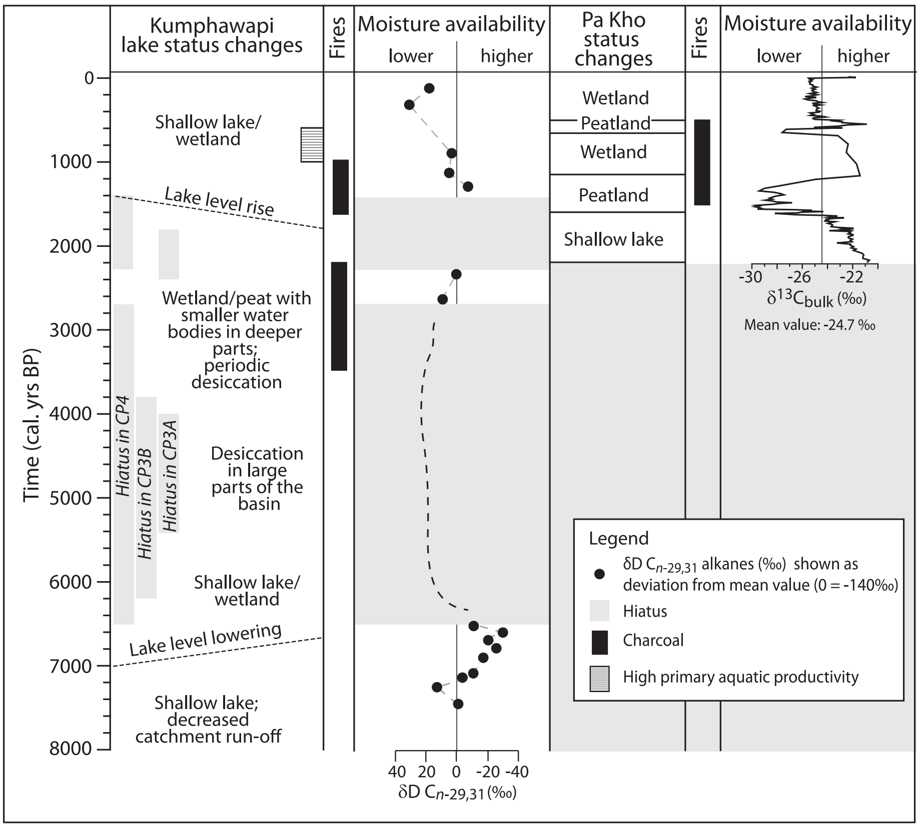

Figure 2. Reconstructed lake status changes and moisture availability for Lakes Kumphawapi and Pa Kho according to Wohlfarth et al. (2012) and Chawchai et al. (2013, 2015a, 2015b). Lake status changes for Kumphawapi were reconstructed by combining the multi-proxy analyses of sediment sequences CP3A, CP3B and CP4 (sediment lithology, chronology, organic and inorganic geochemistry, diatoms); inference of high primary aquatic productivity is based on shifts in $\delta^{13}C_{bulk}$ values and total organic carbon in sequences CP3A and CP4; fires are inferred from macroscopic charcoal in CP3A, CP3B and CP4; hydrogen isotopes (δD) of leaf wax $C_{n\text{-}29,31}$ alkanes were measured on samples from CP4 only. See Chawchai et al. (2015b) for details. Changes in peat composition, biogenic silica and plant macrofossil assemblages of sequence CP3 in Lake Pa Kho allowed reconstructing lake status changes (Chawchai et al., 2015a); fires are inferred from macroscopic charcoal; reconstructed moisture availability is based on shifts in $\delta^{13}C_{bulk}$ values, where less negative values indicate greater contributions from aquatic plants and higher moisture availability and more negative values greater contributions from terrestrial plants and lower moisture availability (Chawchai et al., 2015a). The obvious mismatch between the moisture history reconstructed for Lakes Pa Kho and Kumphawapi during the past 2000 years is because of Kumphawapi's poorly constrained late-Holocene chronology.

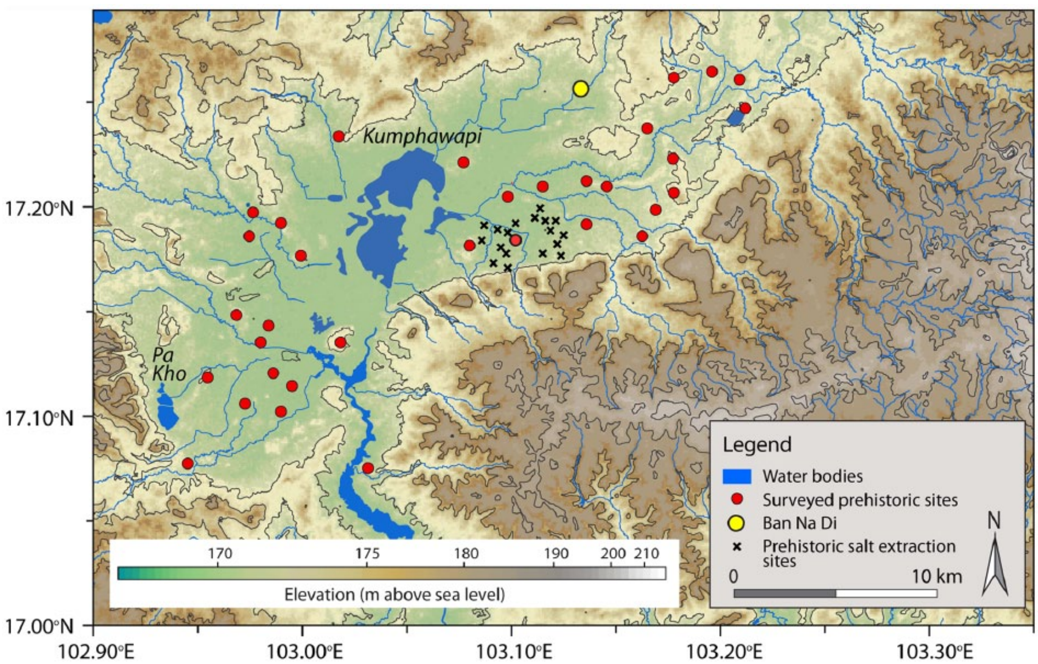

Figure 3. Location of prehistoric sites around Lakes Kumphawapi and Pa Kho discovered during the extensive survey of Higham and Kijngam (1984). Also shown are known salt extraction sites and the location of Ba Na Di, where archaeological excavations were performed (Higham and Kijngam, 1984).

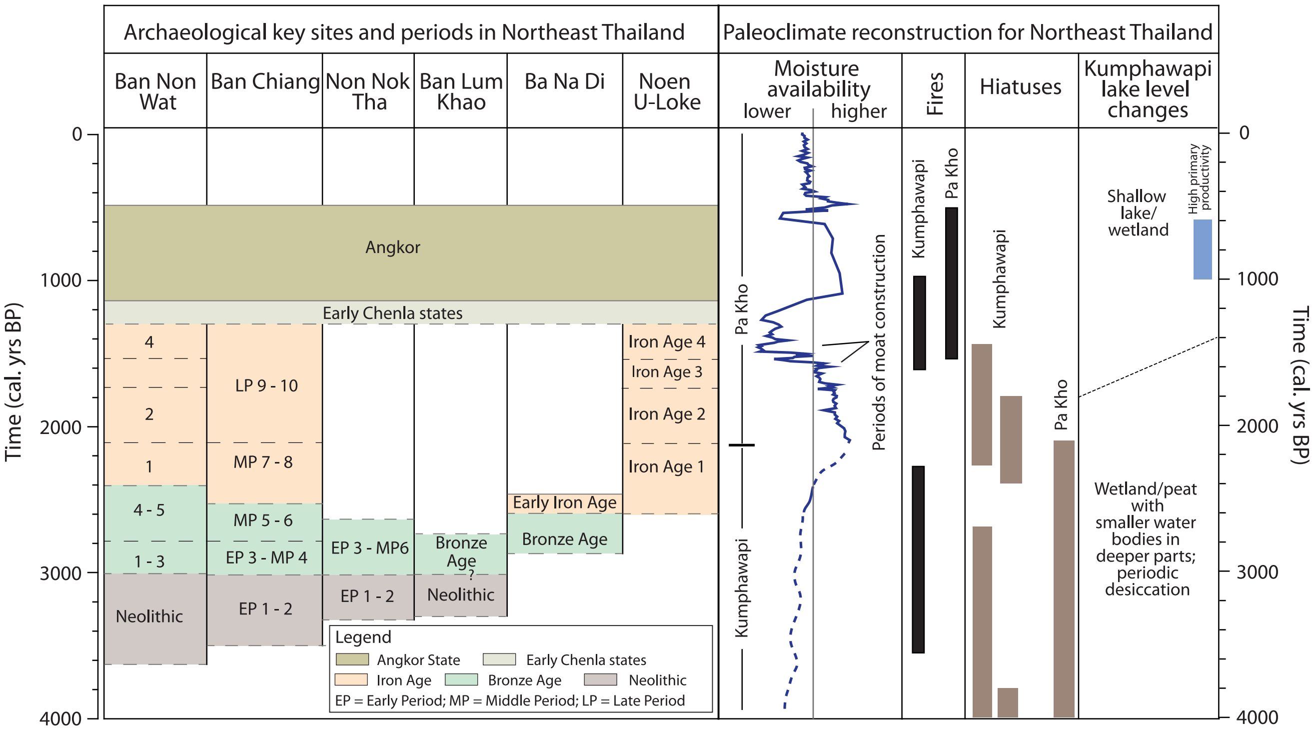

Figure 4. Archaeological key sites and periods in Northeast Thailand compared with palaeoclimate reconstructions for the past 4000 years. The timing of the Neolithic and Bronze Age periods is according to Higham et al. (2015); transitions were placed at the mid-point of the age estimates. The Iron Age periods of Ban Chiang also follow Higham et al. (2015), whereas those for Ban Non Wat, Ba Na Di and Noen U-Loke follow Higham (2014) and Higham and Rispoli (2014). The timing of the early Chenla States is according to Higham (2014). Inferred moisture availability for Lake Kumphawapi is based on a combination of lake status changes and hydrogen isotope analysis and for Lake Pa Kho on $\delta^{13}C_{bulk}$ values. The curves are the same as those shown in Figure 2. Periods of moat construction are according to Higham (2011a). The presence/absence of fires is based on the charcoal record of the Kumphawapi and Pa Kho sequences, and the timing of hiatuses in both lakes is based on the radiocarbon chronology (Chawchai et al., 2015a, 2015b). See also Figure 2 and explanations in the text.

In comparison with other hydroclimatic records from Southeast Asia, Chawchai et al. (2013, 2015b) suggested reconstructed changes in lake status and moisture availability for Lake Kumphawapi can be broadly linked to shifts in the intensity of the Indian Ocean summer monsoon system. Since intervals of increased/decreased early-/mid-Holocene moisture availability compare well with other regional palaeo-proxy records, it can thus be assumed that Kumphawapi's sedimentary record also preserved larger-scale regional climatic changes.

Lake Pa Kho

Lake Pa Kho (17°06′N, 102°56′E; 175 m a.s.l.; Figure 1c) is a dammed lake (<3 km²) that flooded a former wetland (Penny, 2001). The multi-proxy study (lithology, geochemistry, plant macro-remains, grain size, biogenic silica and biomarker analysis) of the 1.5-m-long sediment/peat sequence CP3 is underpinned by 20 ^{14}C dates obtained on selected telmatic and terrestrial macroscopic remains (Chawchai et al., 2015a; Yamoah et al., 2016).

The age model, which was constructed using a Bayesian statistics–based routine, provides overall maximum error margins of ±40–100 years, except for at 1050–1000 cal yr BP (cal. AD 900–950), where error margins increase to ±150–200 years. Chawchai et al. (2015a) suggested two different age models for the Pa Kho sequence, one including a 330-year-long hiatus between 980 and 650 cal. BP (cal. AD 970–1300) and one assuming low accumulation rates across this time interval. Chawchai et al. (2015a) argued that degradation/oxidation of the peat surface during an interval of low moisture availability could have caused the hiatus. However, the assumption of drier conditions during a time interval when plant remains indicate the presence of telmatic and aquatic plants, that is, wetter conditions, seemed difficult to reconcile. Moreover, neither geochemical variables nor stratigraphic changes pointed to a break in peat growth. Therefore, Yamoah et al. (2016) recently put forward the hypothesis that rapid degradation of non-vascular plants, which expanded during wetter conditions, caused the apparent low accumulation rates between 980 and 650 cal. BP (cal. AD 970–1300) and that peat accumulation in Lake Pa Kho was indeed continuous. Specifically, they show that the bulk organic matter is dominated by non-vascular plants. These plant types are more sensitive to biodegradiation, given their soft tissues, which then leads to low mass accumulation rates (Yamoah et al., 2016).

Organic geochemistry, plant macro-remains, grain size and biogenic silica analysis (Chawchai et al., 2015a; Yamoah et al., 2016) allow reconstructing lake status changes for Pa Kho and suggest the existence of a shallow lake between 2100 and 1600 cal. BP (150 cal. BC–cal. AD 350) and alternating peatland (1600–1150 and 650–500 cal. BP or cal. AD 350–800 and 1300–1450, respectively) and wetland phases (1150–650 cal. BP and during the last 500 years; cal. AD 800–1300, since cal. AD 1450; Figure 2). Densely spaced bulk $\delta^{13}C$ measurements, which reflect changes in the contribution of terrestrial and aquatic organic matter (Chawchai et al., 2015a), allow assessing past hydroclimatic conditions in greater detail. Shifts in $\delta^{13}C$ values indicate a gradual decrease in moisture availability between 2120 and 1730 cal. BP (170 cal. BC to cal. AD 220), which was followed by a step-wise decrease between 1730 and 1580 (cal. AD 220–370; Figure 2). Between 1580 and 1500 cal. BP (cal. AD 370–450), moisture availability seems to have fluctuated considerably, as it declined markedly at 1550 cal. BP (cal. AD 400), increased again at 1530 cal. BP (cal. AD 420) and thereafter dropped to lowest values. Between 1500 and 1230 cal. BP (cal. AD 450–720), moisture availability was distinctly lower but increased again around 1150 cal. BP (cal. AD 800) and remained higher between 1110 and 630 cal. BP (cal. AD 840–1320). A shorter interval with distinctly drier conditions is reconstructed between 600 and 560 cal. BP (cal. AD 1350–1390; Figure 2). This was again followed by higher moisture availability, peaking at 500 cal. BP (cal. AD 1450), and by mean values during the past 450 years. The distinct shift seen around AD 2000 is attributed to the recent flooding of Pa Kho's wetland.

Chawchai et al. (2015a) compared the reconstructed local hydroclimatic conditions (as inferred from bulk $\delta^{13}C$ values) with a variety of palaeo-proxy records from the Indian Ocean, the East Asian and Western North Pacific summer monsoon systems and suggested that variations in the strength of summer monsoon rainfall explain the changes in moisture availability observed in the Lake Pa Kho record. However, the distinct shift seen at AD 2000 was likely a response to the recent flooding of the former wetland (Chawchai et al., 2015a).

The occurrence of high amounts of charcoal between 1540 and 470 cal. BP (cal. AD 410–1480) has been linked to agricultural intensification and land-use changes in the region (Figure 2; Chawchai et al., 2015a).

The Neolithic, Bronze Age and Iron Age on the Khorat Plateau

Extensive archaeological excavations have been conducted in the Upper Mun River Valley on the southern Khorat Plateau, where major excavations have been undertaken at the sites of Ban Non Wat, Ban Lum Khao, Noen U-Loke and Non Ban Jak (Figure 1b; see extensive literature review in Boyd and Chang, 2010; Higham, 2011b, 2014, 2015; Higham et al., 2011a, 2011b). Ban Chiang, another famous locality containing Neolithic to Iron Age cultural layers (Pietrusewsky and Douglas, 2002), is located 30 km to the northeast of Kumphawapi (Figure 1b). An extensive archaeological survey in the Lake Kumphawapi region has revealed more than 30 prehistoric (Figure 3) and around 25 historic sites (Higham and Kijngam, 1984). Of these, only Ban Na Di, 8 km to the northeast of Kumphawapi, has been excavated (Higham and Kijngam, 1984), while the cultural assignment for most of the other sites remains uncertain. Non Nok Tha is a third excavated site with a long cultural sequence and lies about 100 km to the west of Kumphawapi (Figure 1b; Bayard and Solheim, 2010).

The new chronological framework for these key sites places Neolithic settlements between 3700 and 3000 cal. BP (1750–1050 cal. BC), and the transition into the Bronze Age is dated to around 3000 cal. BP (1050 cal. BC), with the Iron Age following about five centuries later (2450 cal. BP; 500 cal. BC; Figure 4). Ban Non Wat and Ban Chiang (Figures 1b and 4) are particularly relevant because they were occupied from the Neolithic continuously through to the late Iron Age (3600–1400 cal. BP; 1650 cal. BC–cal. AD 550; Higham, 2011a; Higham et al., 2015).

The Neolithic and Bronze Age

Early Neolithic farmers, who originated in the Yangtze Valley, reached Northeast Thailand around 3700 cal. BP (1750 cal. BC; Higham, 2014; Higham et al., 2015), where they may have interacted with indigenous hunter-gatherer communities. The early Neolithic farmers brought with them a full-developed agricultural economy that centred on rice cultivation and raising pigs, cattle and dogs. Fishing, hunting and collecting were also significant. The established technology included fine ceramics, weaving and polished stone adzes (Higham, 2014; Higham et al., 2011a).

The transition into the early Bronze Age in the 11th century BC has been identified at Ban Non Wat, Ban Chiang, Non Nok Tha and Ban Lum Khao (Figure 1b and 4; Higham et al., 2015). At Ban Non Wat, the early Bronze Age is marked by a dramatic rise in mortuary wealth as grave goods now include exotic marble and marine shell jewellery, copper tools and ornaments (Higham, 2011a). The distinct change in mortuary goods suggests an increase in wealth and ownership of exotic valuables, an ability to control resources and the creation of a surplus and, as such, a degree of social ranking (Higham, 2011a). Isotope analyses on teeth from early Bronze Age burials at Ban Non Wat show that these people had a broad-spectrum diet and a greater reliance on C_3 crops, such as rice, which lends support to rice agriculture (King et al., 2013). The rise in mortuary wealth is also seen at the nearby site of Ban Prasat, but further to the north, remote from natural exchange routes, the Bronze Age burials at Ban Na Di, Ban Chiang and Non Nok Tha were modestly endowed with mortuary offerings. The last two Bronze Age phases at Ban Non Wat (c. 2800–2400 cal. BP or 850–450 cal. BC; Figure 4) witnessed a sharp decline in mortuary wealth. Copper-based offerings became rare and many graves contained only few ceramic vessels and shell beads (Higham, 2011a). Plant remains studied at Non Ban Jak now included wet field weeds (Higham et al., 2014), and isotope analyses point to a change in subsistence strategy as meat and C_4 crops may have become supplements to the rice diet (King et al., 2013).

The Iron Age

The transition from the late Bronze Age into the early Iron Age is dated to between 2600 and 2400 cal. BP (350 and 450 cal. BC) in Ban Non Wat, Ban Chiang and Ban Na Di (Figure 4; Higham, 2014; Higham et al., 2015). In the Upper Mun River Valley, four Iron Age phase (IA 1–IA 4) have been defined based on the excavations of Ban Non Wat, Noen U-Loke and Non Ban Jak. Iron Age phases IA 2 to IA 4 are, however, best represented at Noen U-Loke (Figure 4; Higham, 2011a).

At Ban Non Wat, there was a seamless transition from the late Bronze Age cemetery into the IA 1 cemetery. Mortuary traditions and the form of the ceramic vessels placed with the dead remained unchanged, but the first iron weapons, tools and ornaments were found, together with rare ornaments of glass, carnelian and agate. Bronzes now became more abundant and included ornaments cast by the lost wax technique (Higham, 2011a, 2014). Food remains placed as mortuary offerings included an abundance of fish and a significant number of domestic water buffalo bones. The large sample of graves was disposed in two groups with differing orientations of the body, but neither included significantly wealthy individuals nor groups. As with the late Bronze Age, there is little evidence for social ranking (Higham, 2011a).

The second Iron Age phase (IA 2; c. 2100–1750 cal. BP or c. 150 cal. BC–cal. AD 200) at Noen U-Loke (Figures 1b and 4; Higham, 2011a; Higham and Rispoli, 2014) involved two groups of graves that evidence new and exotic mortuary offerings and elaborated mortuary rituals. The dead were interred in graves filled with rice and accompanied by agate, glass and carnelian jewellery and abundant bronzes (Higham, 2011a, 2014).

With IA 3 at Noen U-Loke (1750–1550 cal. BP or cal. AD 200–400) (Figures 1b and 4; Higham, 2011a; Higham and Rispoli, 2014), we encounter four groups of graves, three of which display a sharp increase in wealth as seen in a remarkable quantity of bronzes (Higham, 2011a, 2014). One man was buried wearing silver and gold ear coils, 150 bangles, three belts, 67 finger rings and four toe rings, and a woman in a second nucleus of burials wore a necklace of 68 gold and many agate beads (Higham, 2011a, 2014). One man in this group was accompanied by a heavy socketed iron ploughshare. Yet a third group of burials was markedly poorer and dominated by spindle whorls as offerings. It is considered highly likely that these clusters of graves contain individuals linked through descent and that the outstandingly wealthy individuals were seen as socially dominant (Higham, 2011a, 2014). The rise in wealth occurred at a time when there is growing evidence for a major agricultural revolution that involved the

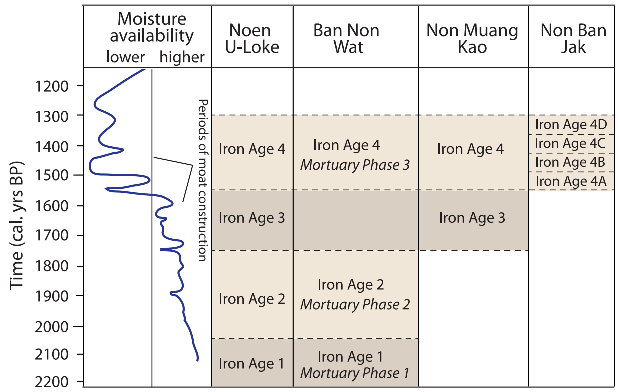

Figure 5. Reconstructed moisture availability for Northeast Thailand during the past 2000 years (Chawchai et al., 2015a) compared with the chronology of the Iron Age on the Khorat Plateau (Higham, 2011a, 2014; Higham and Rispoli, 2014). Inferred moisture availability is based on the $\delta^{13}C_{bulk}$ curve for Lake Pa Kho shown in Figure 2. Periods of moat construction are according to Higham (2011a).

cultivation of rice in fixed, irrigated fields. The discovery of water buffalo and cattle hoof prints at Noen U-Loke suggests the presence of a pound for domestic stock within the settlement, and through the discovery of iron ploughshares, the opening of an increased area under cultivation by ploughing. This third Iron Age phase coincides with large-scale forest clearance in the upper Mun River Valley (Boyd, 2008; Boyd and McGrath, 2001; McGrath and Boyd, 2001), moat/reservoir constructions (Scott and O'Reilly, 2015), iron forging and industrial-scale salt production (Higham, 2014; Nitta, 1992; O'Reilly, 2008). This was also a period when the quantity of iron weaponry increased. Again, the density of moated settlements in the Mun River Valley and the demographic profiles strongly suggest a marked population growth during this later Iron Age period (Higham, 2014).

Iron Age phase 4 (1550–1300 cal. BP or cal. AD 400–650; Higham, 2011a; Higham and Rispoli, 2014) is best represented at Noen U-Loke and Non Ban Jak (Figures 1b and 4). The former saw a new configuration of burials, in that they were laid out in a dispersed manner, quite unlike the tight nuclei of the previous phase. The reason for this pattern becomes clear when turning to Non Ban Jak (Higham et al., 2014). This site was occupied throughout IA 4, and the occupation and mortuary sequence falls into four sub-phases, IA 4a–d (Figure 5). Unlike Noen U-Loke, the foundations of house walls could be traced, and within these one finds the floors of a series of rooms. The dead were buried within these residences. Non Ban Jak comprises two distinct mounds within a double set of moats, and within one of these, the houses became very substantial with time (Higham et al., 2014). One contained a ritual room containing the graves of an adult, a child and an infant, while lidded pots had been placed in at least three of the four corners. On the other, western mound however, the houses were less substantially constructed, and burials were cut through the clay floors. The IA 4 burials at Noen U-Loke and Non Ban Jak were not as richly endowed as during IA 3, but they were not markedly poor (Figure 6; Higham et al., 2014). There was gold, lead, carnelian, agate and bronze jewellery, and iron tools and weapons (knives, sickles and spears). At Non Ban Jak, rice survived in burials as pseudomorphs on the corroded surfaces of the iron artefacts, reminding us that a further socketed iron ploughshare had been found in one of the ceramic kilns at this site (Higham et al., 2014). The importance of this new practice of residential burial lies in the widespread reflection of a means to project and sustain corporate status and assets.

The size of late Iron Age settlements on the Khorat Plateau can be estimated by calculating the areas within the innermost moat (Higham, 2014; McGrath et al., 2008). These mounds, which ranged from 0.5 to 171 ha, with a mean of 15.9 ha (Scott and O'Reilly, 2015), reached a height of about 3–5 m above the extensive, flat floodplain. The moats were shallow (tens of centimetres), but the channels were wide (30–60 m) and contained within raised banks (McGrath et al., 2008). The exact purpose of the moats is still under discussion (O'Reilly, 2008; Scott and O'Reilly, 2015). It has been suggested that they were made in response to less reliable water supply and severe drought (Boyd, 2008; Boyd and McGrath, 2001; McGrath and Boyd, 2001); that they could represent defence features, changed agricultural practices, flood mitigation because of stronger monsoon rains and competition over resources (O'Reilly, 2008); that they were used to control water supply and thus represent a human response to increased water availability (McGrath et al., 2008); and that they represent water storage facilities that allowed surviving dry seasons and drought (Scott and O'Reilly, 2015).

The investment in and organisation of labour are best reflected in the size and complexity of these new moat/reservoir systems of water control. Ban Non Wat had at least two moats and banks with a linear length of 75 m, Noen U-Loke was ringed by five concentric moats 150 m wide and the moats and banks at Non Ban Jak were 80 m wide (Higham, 2011a). Moreover, air photographs reveal the presence of dams and water distribution systems through possible canals beyond the outermost moats (Parry, 1992). Given the differentiation between wealthy and poor groups of burials at Noen U-Loke, it is hard to avoid the conclusion that the greatly increased production of rice, iron and salt reflects a sharp rise in social ranking during this vital period.

Most of the moated late Iron Age sites were abandoned around 1400–1350 cal. BP (cal. AD 550–500; Figure 5) and new centres, such as Phimai, were founded. The abandonment of late Iron Age sites has been discussed widely by Boyd (2008) and Boyd and Chang (2010). Boyd (2008), based on palaeoenvironmental studies in the Mun River Valley, argued that the social and environmental changes seen during the late Iron Age were a response to increasingly variable and less reliable water supply. Higham (2014), on the other hand, speculated that the increase in conflicts and warfare during the final phase of the late Iron Age could have led to absorption of populations into new centres.

The archaeological record for the Iron Age in the area surrounding Lake Kumphawapi (Figure 3) is less well documented. Certainly, the number of moated sites thins out as one reaches the valley of the Chi River and they disappear in the Sakon Nakhon basin, drained by the Songkhram River. However, there were many Iron Age settlements, and at Ban Na Di and Ban Chiang (Figures 1b and 3), excavations have uncovered burials that, while never approaching the wealth of those in the Mun River Valley, still contained some exotic glass ornaments and fine ceramic vessels. The faunal remains also reflect an economic base that included rice cultivation; the raising of domestic cattle, pigs and water buffalo; and much reliance on fishing and hunting (Higham and Kijngam, 1979).

The Chenla and Dvaravati microstates and the Angkor Empire

It was in the context of late Iron Age communities that small states, belonging to the Chenla and Dvaravati period (1400–1150 cal. BP or cal. AD 550–800) arose, followed by the Khmer Empire of Angkor (1150–520 cal. BP or cal. AD 800–1430) (Figure 4; Higham, 2014; Welch, 1989, 1998). Apart from the continuity seen at Non Ban Jak, the Chenla period is evidenced at Phimai, where excavations have unearthed brick foundations (Welch, 1989, 1998) overlying late Iron Age remains (Talbot and Janthed, 2001). The Angkorian temple of Phanom Wan was constructed above Chenla brick structures and an Iron Age cemetery (Higham, 2014).

Figure 6. Burial 82 from Iron Age 4 at Non Ban Jak reveals the wealth deployed during mortuary rituals and is the richest grave found during mortuary phase 3 (see Figure 5). This man, for example, wore two sophisticated bronze belts, three earrings and one bimetallic ring of bronze and iron. Grave goods included six pottery vessels, two bivalve shells, an iron sickle and an iron knife blade (Higham et al., 2014). Contemporaries at this site and at Noen U-Loke also wore ornaments of gold and silver.
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Sanskrit and Khmer inscriptions of the Chenla–Dvaravati period reflect a social organisation that developed from the late Iron Age. There were elite leaders known as *pon*, specialist rice field workers, weavers, potters and smiths, as well as water reservoirs and the mention of rice fields (Higham, 2014). In the early 9th century, the competing small states or complex chiefdoms were unified by King Jayavarman II (Higham, 2014). The Khmer civilisation then flourished until about 650 cal. BP (cal. AD 1300), when the court vacated Angkor in favour of a new centre near the modern capital. This move has been attributed to changing climate conditions, such as drought or extremely variable precipitation patterns that severely affected the complex water control mechanisms (Evans et al., 2007; Kummu, 2009) at and around Angkor (Buckley et al., 2010, 2014; Cook et al., 2010).

Discussion

Moisture availability reconstructed for the past 8000 years suggests that the Khorat Plateau experienced wettest conditions between 7000 and 6600 cal. BP (5050–4650 cal. BC) and that moisture availability decreased thereafter (Figure 3). The observation that sediments did not accumulate in Lake Pa Kho until about 2100 cal. BP (150 cal. BC) and the presence of multiple hiatuses in Lake Kumphawapi's sedimentary sequences between 6400 and 1800 cal. BP (4450 cal. BC–cal. AD 150) indicate that hydroclimatic conditions were overall much drier during the Neolithic, Bronze Age and early Iron Age (Figure 4). Shorter time windows in Lake Kumphawapi with slightly higher moisture availability (c. 2400 cal. BP; c. 450 cal. BC) compare in time to finds of crocodile bones among the late Bronze Age mortuary offerings at Ban Na Di, located 8 km to the northeast of the lake basin (Figures 3 and 4; Higham and Kijngam, 1984). The presence of shell middens and large amounts of fish bones at Ba Na Di as early as c. 2800 cal. BP (c. 850 cal. BC; Higham and Kijngam, 1984), however, suggests that water bodies must have existed in the Kumphawapi lowland. Frequent finds of charcoal in Kumphawapi's sediments could relate to forest clearances by Neolithic and Bronze Age populations, but could also derive from natural forest fires since climatic conditions were distinctly drier during these time intervals (Figure 4). In comparison with the Upper Mun River Valley on the southern Khorat Plateau (Figure 1b), where widespread forest clearance only started during the late Bronze Age (Boyd, 2008; Boyd and McGrath, 2001; McGrath and Boyd, 2001; McGrath et al., 2008), we thus speculate that much of the charcoal recovered from Kumphawapi's sediments is due to natural forest fires.

The pollen, phytolith and charcoal record for Lake Kumphawapi has been used to argue for anthropogenic activities predating the Bronze Age (Kealhofer and Penny, 1998) and for an early start of the Bronze Age in Thailand (White, 2008). Moreover, Kealhofer (2002) suggested that the phytolith record from Kumphawapi could reflect a shift in land management and an increase in rice weed fields and would as such provide evidence for agriculture in the region already around 5000–4500 cal. BP (c. 3050–2550 cal. BC). However, as shown by Wohlfarth et al. (2012) and Chawchai et al. (2013, 2015b), the multiple long hiatuses in the Kumphawapi sequences between c. 6400 and 1800 cal. BP (c. 4450 cal. BC–cal. AD 150; Figures 2 and 4) rule out such conclusions. The record of Kumphawapi cannot be used as an argument for early human disturbances and/or early rice cultivation.

The start of sediment accumulation in Lake Pa Kho around 2100 cal. BP (c. 150 cal. BC) and the re-establishment of a shallow lake in the Lake Kumphawapi basin a few hundred years later (Figure 4) signal a return to higher moisture availability, likely because of a strengthening of the summer monsoon (Chawchai et al., 2015a; Wohlfarth et al., 2012). The reconstructed change in hydroclimatic conditions from drier to wetter seems to have occurred during Iron Age phase 1, and the subsequent interval with higher moisture availability continues throughout Iron Age phase 2 (Figure 4). This is a period when the first burials were interred in rice-filled graves (Higham and Kijngam, 2007). However, there are too few burials at Noen U-Loke to indicate whether there was a significant change compared with the clear lack of any elite burials in the preceding Iron Age phase 1 at Ban Non Wat (Higham and Kijngam, 2012).

Pa Kho's $\delta^{13}C$ record suggests that moisture availability gradually declined between 1730 and 1580 cal. BP (cal. AD 220–370), abruptly decreased at 1550 cal. BP (cal. AD 400), increased again at 1530 cal. BP (cal. AD 420) and subsequently declined to low levels at 1500 cal. BP (cal. AD 450; Figures 4 and 5). These shifts, which have been linked to variations in summer monsoon strength (Chawchai et al., 2015a), compare in time to Iron Age phases 3 and 4 (Figure 5). Iron Age phase 3 witnessed a growing population and social ranking, that was based on an agricultural revolution that involved the construction of reservoirs, the reticulation of water into fixed rice fields, ploughing and the intensification of production through iron technology (Higham, 2011a, 2014). We also find evidence for conflict, salt production on an industrial scale and the ritual use of surplus rice in mortuary rituals (Higham, 2011a, 2014; Nitta, 1992). The appearance of large amounts of charcoal in Kumphawapi's sediments (c. 1600 cal. BP or c. cal. AD 350) and in Pa Kho's peat (c. 1540 cal. BP or c. cal. AD 410; Figure 4) could therefore point to large-scale deforestation for agricultural purposes, similar to what has been reported for the Upper Mun River Valley (Boyd, 2008; Boyd and McGrath, 2001; McGrath and Boyd, 2001).

The apparent temporal coincidence between a gradually weaker summer monsoon and the marked social changes that took place during Iron Age phase 3 makes it tempting to speculate that Iron Age societies adapted to the decline in moisture availability. We also observe that the first period of moat construction falls close in time to when summer monsoon strength decreased markedly (Figure 5). Since both chronological frameworks have their specific uncertainties – calibrated maximum error margins for the palaeoclimate data set of Lake Pa Kho are ±100 years at 1750–1730 cal. BP (cal. AD 200–220; start of IA 3) and ±60–70 years at 1580–1550 cal. BP (cal. AD 370–400; end of IA 3) – precise correlations are hampered. Nevertheless, the close coincidence between moat construction and hydroclimatic changes adds a new facet to the on-going discussion on why the moats were put in place. It supports suggestions that these constructions represent water storage facilities and reservoirs (e.g. Boyd, 2008; Boyd and McGrath, 2001; McGrath and Boyd, 2001; Scott and O'Reilly, 2015) to irrigate the surrounding rice fields and to maintain production when monsoon rains faltered (Higham, 2014).

The stressful situation created by marked changes in the strength of the summer monsoon and increased drought could have been the trigger or stimulus to what is seen in terms of social changes during Iron Age phases 3 and 4. It would have placed a premium on the ownership of the best land open to irrigation. Those who occupied the houses at Non Ban Jak, for example, interred their dead within the living quarters, together with their iron sickles (Higham et al., 2014). Residential burial thus projected corporate ownership of vital resources. There was also increased conflict between Iron Age communities as seen in the forging of spears and arrowheads (Higham et al., 2014).

We suggest that the environmental stress caused by a gradually weaker summer monsoon and subsequent drought phases was met by a strong social response manifested in the control of water, the expansion of the moat reservoirs and the rise in social elites that were soon to be translated into the lineages of the *pon*, leaders of the Chenla early states. The later Iron Age thus displays resilience and adaptation to a dramatically changing climate, involving deeply significant social changes that, we argue, generated a rapid transition into the early socially hierarchic polities of the Chenla and Dvaravati states.

Our view is markedly different from that expressed, for example, by Boyd (2008) and Boyd and Chang (2010), who argued that late Iron Age settlements in the Mun River Valley were abandoned because populations had over-exploited their resources through forest clearance and intense landscape management. Widespread human impact, increased soil erosion and drought would have hampered the regeneration of woodlands, which together with increasingly variable and less reliable water supply would have led to the decline and abandonment of late Iron Age settlements (Boyd, 2008; Boyd and Chang, 2010). Archaeological and historical evidence, however, argues against the abandonment of late Iron Age settlements, since many of the moated sites continued to exist and still exist today. Moreover, irrigated rice does not overexploit resources and has the capacity for continuous cropping provided that there is sufficient water.

Reconstructed moisture availability remained low until c. 1230 cal. BP (c. cal. AD 720), but increased again between c. 1230 and 1110 cal BP (cal. AD 720–840), that is, during the time interval corresponding to the early phase of the Chenla and Dvaravati states (Figure 5). The long interval with higher, but gradually declining, moisture availability between 1110 and 630 cal. BP (cal. AD 840–1320) and strongly variable moisture availability between 630 and 500 cal. BP (cal. AD 1320–1450; Figure 4) coincide in time with the rise and expansion of the Khmer Empire and its later demise. The link between hydroclimatic shifts and the rise and fall of the Khmer Empire has been discussed extensively by Buckley et al. (2010, 2014), Cook et al. (2010) and Lieberman and Buckley (2012), since water and water availability played a large role for Angkorian societies. By using an updated version of the high-resolution Monsoon Asia Drought Atlas, Buckley et al. (2014) recently lend support to the hypothesis that climate variability, that is, shifts between prolonged droughts and anomalously strong rainfall, over short time intervals could have caused societal instabilities in the Khmer Empire. However, they also conclude that extreme rainfall events combined with a disregard for repairing Angkor's hydrological infrastructures could have ultimately led to the abandonment (Buckley et al., 2014).

The chronology of our palaeoclimate and archaeological data sets are, however, too coarse to discuss the exact temporal correlation between certain events during the Bronze Age and Iron Age, as has been done for the historical period in Southeast Asia (e.g. Buckley et al., 2010, 2014; Cook et al., 2010; Lieberman and Buckley, 2012). Moreover, we can only reconstruct shifts in moisture availability and, as such, in summer monsoon strength on a qualitative basis. Despite these shortcomings, the coincidence between a gradual weakening of the summer monsoon, subsequent distinct shifts between drier and wetter conditions and finally, the overall lower moisture availability and the social changes that are seen during the late Iron Age in Northeast Thailand are striking.

Conclusion

The integration of Holocene palaeoenvironmental and archaeological sequences in Northeast Thailand allows a discussion of the relationship between climate and human resilience and adaptation. We show that the intensity of the summer monsoon has varied during the past 10,000 years and that multiple short-term fluctuations were superimposed on the overall gradual decline in summer monsoon strength. Settlement by Neolithic rice farmers began about 3700 cal. yr BP (c. 1700 cal. yr BC) and was succeeded by Bronze Age settlers around 3000 cal. yr BP (c. 1000 cal. yr BC). The subsistence of Neolithic and Bronze Age farmers was based on dry land rice cultivation, supplemented by fishing, hunting, gathering and the maintenance of domestic pigs and cattle. Comparisons of the cultural sequences with the palaeoclimatic changes reconstructed from the sedimentary record of Lake Kumphawapi suggest that moisture availability was low and that climate conditions were dry. Approximately coincident with the start of the Iron Age around 2600–2400 cal. yr BP (c. 350–450 cal. yr BC), moisture availability increased again and remained higher throughout the first two Iron Age phases. The marked decline in moisture availability c. 1580 cal. yr BP (c. 370 cal. BC) and subsequent lower moisture availability (1550–1150 cal. yr BP; cal. yr AD 400–800) compare in time to Iron Age phases 3 and 4 and the Chenla–Dvaravati states.

Iron facilitated forest clearance and populations began to expand. Distinct social changes can be seen with the start of Iron Age phase 3: the forging of iron ploughshares and sickles, the construction of moat/reservoirs around villages and towns, the construction of permanent bounded rice fields, the application of water buffalo to bring fields under cultivation by ploughing, the rise in wetland weeds, the growth in iron weaponry and the presence of social elites.

We argue that these deep-seated cultural changes coincided with and were adaptations to increasing aridity. This agricultural revolution laid the foundations to the formation of early state societies by the 6th century AD. These early kingdoms and their successor, the Angkorian Empire, were reliant on water control and irrigation to feed the extensive rice fields.

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