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The Early Rice Project: From Domestication to Global Warming

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The Early Rice Project, at the UCL Institute of Archaeology, is clarifying the origins of Asian rice agriculture. In the Lower Yangtze region of China, we have found the tipping point when domesticated forms first outnumber wild types c.4600 BC. Investigations of assorted weed flora are also revealing how the cultivation of rice changed over time, with early cultivation in small, irregular, dug-out paddy fields in the Lower Yangtze from c.4000 BC, providing a means for the careful control of water conditions. We also work on early rice cultivation in Thailand and India. By better characterising how rice was cultivated across its entire range, we aim to model the ancient output of atmospheric methane from wet rice fields, as this was a potential contributor to the long story of human-caused global warming.

Much of Asia depends on rice as a staple food, and so it has been for some thousands of years. Rice growing regions of East Asia, South-East Asia and the Indian subcontinent boast the world's highest population densities, and this is possible in large measure because of rice. While rice has featured in the agriculture of South and East Asia since prehistoric times, recent archaeological research has offered to new insights and raised new questions about when, how and why rice first came to be cultivated. The Early Rice Project at the UCL Institute of Archaeology is contributing to our new understanding of how a shallow water wild grass became the world's most productive crop, and an economic staple in the civilizations of Southern and Eastern Asia.

Our work explores a number of aspects of rice, including domestication, the development and diversification of systems for cultivating rice, the spread of rice farming, and the potential global impact of rice cultivation as it came to contribute to rising levels of the greenhouse gas methane over the past 5,000 years. Our methods include the study of plant macro remains (seeds and chaff) and phytoliths (plant silica bodies) from archaeological sites, and the collection of comparative data from modern fields of traditional rice cultivation and wild rice stands in India, Thailand and China.

Raw materials for rice farming: wild rices of Asia

Before farming began hunter-gatherers must have had traditions of exploiting the wild ancestors of rice. It is therefore essential that we have an understanding of the wild habitats of rice, how this might have differed in climatic conditions of the past (especially from 10,000–6,000 years ago), and consider how technologically people exploited this wild food resource. Wild rice progenitors include two ecological types, an annual grass on monsoon-filled seasonal puddles and floodplain margins (*Oryza nivara*) and a perennial of permanent pools (*Oryza rufipogon*). Both of these

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species are distributed across parts of India, South-East Asia and southern China, but their particular distributions at a local geographical level differ, with the wild annual being more frequent in tropical monsoon regions such as India and the perennial more frequent in the river valleys and lakes of South-East Asia and South China. The perennial wild rice is the likely progenitor of domesticated East Asian rices (subspecies *japonica*), while the annual is implicated in the distinct origins of South Asian rices (subspecies *indica*).

The modern distribution is a product of environmental history, including both long-term climatic changes and human modifications of the environment. This means that the modern distribution is an imperfect reflection of the original distribution of wild rice at the time people first began to cultivate rice. We know from palaeoclimatic data that temperatures were and higher and rainfall was higher on average between 10,000 and 6,000 years ago, and we therefore expect that wild rices were somewhat more widespread, extending further north in China and somewhat further west and south in India. In addition, humans have modified the environment through the destruction of good habitats for wild rice. Many such areas, around lakes and in river valleys have been turned to agriculture with pre-existing wild vegetation, including wild rice removal. Chinese historical sources indicate that wild rice used to occur much further north, around local water bodies in the Shandong province for example, as late as China's Song Dynasty (10th century). Thus the Lower to Middle Yangtze river valley and areas of eastern China just to the north look like prime locations to find the archaeological sites of the earliest rice cultivators (**Fig. 1**).[1]

The domestication of rice in the Yangtze Delta

Archaeologists and botanists have long debated the origins of rice. For many archaeologists who focus on East Asia or South-East Asia, it has long appeared that rice agriculture began in South-Central China, somewhere along the Yangtze River, and spread from there southwards to Indo-China and Malaysia and to the north-east towards Korea and Japan. However, archaeologists working in India have argued that their evidence suggests an origin of rice cultivation in the Ganges river valley, by peoples unconnected to those of the Yangtze. For both regions there are current controversies about how early rice was cultivated, and how best to identify when rice was domesticated as opposed to being gathered wild. One challenge has been to have reliable criteria that can be applied to archaeological remains and, unfortunately, the charred grains that are so often the main archaeological evidence are poorly diagnostic on their own. Improved methods of archaeobotany are providing new insights into how domesticated rice evolved, by providing a means of tracking key changes in the chaff of rice, in particular the spikelet base.

Fig. 1: Studying the ecology of wild rice in India: Indian colleague Prof. Kajale surveys wild rice (*Oryza rufipogon*) and associated species in Orissa.

Fig. 2: A comparison of wild rice shattering (left) and non-shattering domesticated rice (right), with insets of archaeological spikelet bases of the wild and domesticated types from the Chinese Neolithic site of Tianluoshan; the location of a spikelet base on modern rice examples is indicated by an arrow.

The beginning of cultivation was when human behaviours changed, and *domestication* was when the plant itself subsequently changed to become a better crop. There was a linked process of evolution in technology (that of cultivation) and the evolution of new adaptations in the rice plant. One of the key changes in most domesticated grain crops is a shift from natural seed dispersal (the shattering of the ear or panicle) to a dependence on human dispersal. This makes the domesticated species dependent on the farmer for propagation. More generally, it substitutes human labour for natural dispersal mechanisms, but makes the take of the harvester much greater. Based on recent research by geneticists, this change is known to be caused by one of a few genetic mutations that affect the formation and timing of the split between the rice spikelet (the grain contained in its husk) and the stalks of the mother plant. The archaeological recovery of the base of the spikelet allows a direct identification to be made of whether an ancient rice spikelet was shed naturally, in the wild way, or was torn off by human threshing of a domesticated plant. Some spikelet bases also fall into a more ambiguous ‘immature’ state. Because grain maturation is gradual, over a period of a few weeks, our expectation is that in wild rice harvested by gatherers only wild and immature types should be present. Once people began to cultivate rice and evolution favoured adaptations to farmers’ harvests, the domesticated form would have increased as a proportion of the population towards complete dominance of the samples (**Fig. 2**).

With an increase in systematic archaeobotanical sampling by flotation and wet-sieving to smaller size fractions (down to 0.3mm), we have begun to recover quantities of the remains of spikelet bases. With improved recovery methods and careful sorting of minute plant remains, we were able to recover more than 2,600 rice spikelet bases from the Chinese site of Tianluoshan and,

Fig. 3: A view of Tianluoshan (c.5000–4200 BC) after the 2007 excavations by the Zhejiang Province Institute of Archaeology – note the waterlogged preservation of wood construction timbers and a canoe paddle (lower right); archaeobotanical studies on this site are being carried out at the UCL Institute of Archaeology.

since then, thousands of spikelet bases have been recovered in our work across more than a dozen sites in China, Thailand, India and Sri Lanka. At last we have a basis to characterize the proportion of various rice types in past populations and the rate at which domesticated rice evolved and the rate at which wild types of seed-shedding were reduced in the rice harvested at ancient sites.

Tianluoshan (near Hangzhou, China) catches a key point, where the evolutionary process of domestication was underway and when a key tipping point in the process occurred.[2] The lower layers at this site date from c.4900 BC to 4600 BC and show sequentially an increase in the proportion of domesticated rice bases from 27% to 36% to 39%, wild and immature forms both declined in percentage. In other words, these samples capture the middle of the process of rice domestication. It should be noted that rice remains from this site are still outnumbered by fragments of nutshell, from acorns and *Trapa* water chestnuts, indicating that early rice cultivation developed for many centuries alongside the gathering of wild plant foods. The large quantities of wild nuts, alongside fish-bones and hunted deer suggest a predominantly hunter-gatherer-fisher lifestyle, and that only with later cultivation and domestication of rice, perhaps closer to 4000 BC, did people give up gathering as many nuts and focus on farming rice. Sampling from archaeological excavations of earlier and later sites in the region should help to fill in the beginning and end of this process. At least for later stages of the processes additional archaeobotanical evidence we have collected from another site, Caoxieshan, from c.4000–3800 BC, indicates that by this time rice alone dominated the plant food economy: acorns and water chestnuts are conspicuously absent, and the spikelet bases of rice indicate a secure majority (>70%) was of the domesticated type, while immature types were few, and wild forms were at around 20%, a proportion we expect to persist because weedy forms of rice usually infest the crop. Caoxieshan also provides important evidence for the techniques of how early rice in China was cultivated. Caoxieshan preserved small paddy field systems, which indicate that c.6,000 years ago rice was grown in small ovoid fields just a few meters across, dug down into sterile ground (**Fig. 4**). Such fields would have allowed the tight control of water levels and soil fertility, which were important aspects of early rice management as it became domesticated.[3]

How was early rice cultivated?

There are potentially many different forms of rice cultivation, including artificial wetlands (paddy-fields), cultivation on natural monsoon rains and river inundation and even inclusion of rice in slash-and-burn agriculture of some tropical mountain regions. Which of these systems of cultivation came first is a question that is becoming answerable. Our Early Rice Project aims to develop and refine methods for answering this question, but not through the study of archaeological rice remains but instead through the seeds of associated flora, i.e. the weeds that grew in the field with the rice.

While the rice crop has been adapted to many different methods of cultivation, the weeds that co-occur with rice are usually more limited in the range of conditions they tolerate. Indeed, to some degree the development of cultivation methods has been driven by the war of farmers on weeds: ploughing helps eliminate more perennial species; flooding rice fields during early growth eliminates those weeds which cannot tolerate standing water, while drying rice part way through the growing cycle may help to reduce the competition of wetland weeds. For this reason we have been studying a range of modern traditional rice cultivation systems, in China, Thailand and India, with a preference for those out of the way places where farmers have limited or no use of modern industrial herbicides. In such fields we can survey which weeds grow alongside rice under different regimes of water depth and cultivation type. In addition, the soils of such fields contain assemblages of microscopic phytoliths that reflect the community of rice and its weeds that is found in those particular circumstances (**Fig. 5**). These modern analogues, when they are counted at the microscope and compared through multivariate statis-

Fig. 4: A trench at Caoxieshan (Jiangsu, China), excavated by Suzhou Museum in 2008, in which the distinctive fill in the small rice field units is visible.

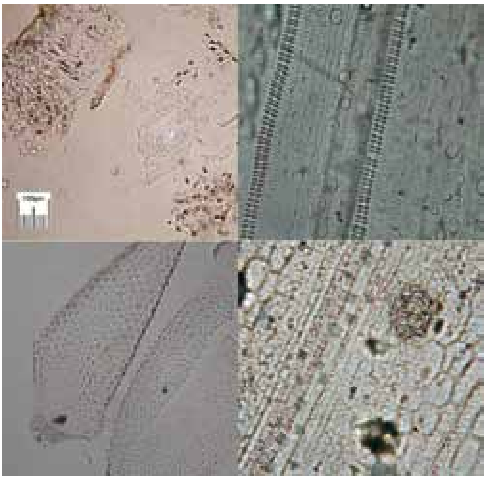

Fig. 5: Examples of phytoliths from rice weeds that have been gathered as part of our modern analogue collection, clockwise (from top left) *Brachiaria ramosa* grass husk, *Leersia hexandra* leaf, *Ischaemum rugosum* grass leaf, *Cyperus pilosus* sedge nutlet pericarp.

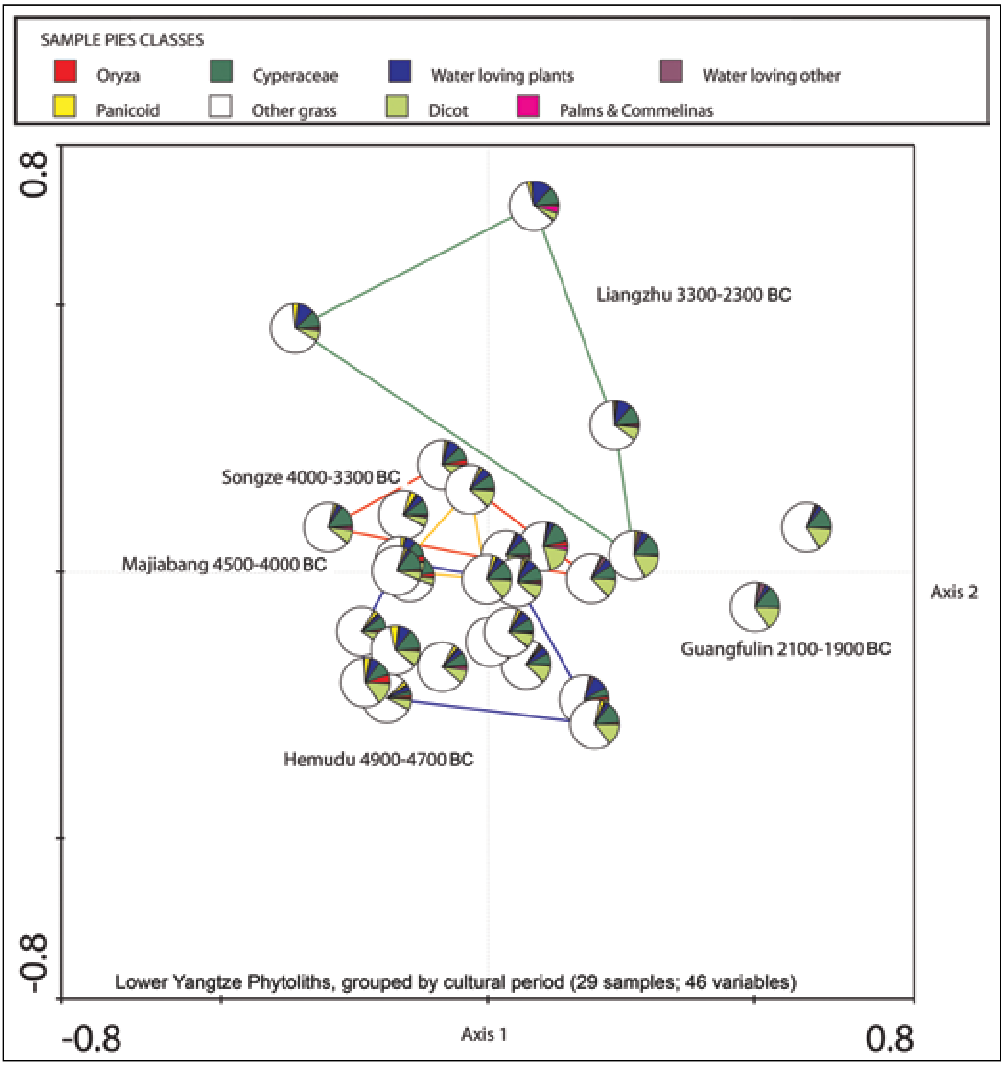

Fig. 6: Results from multivariate statistics (correspondence analysis) on archaeological phytolith samples from five sites in the Lower Yangtze region of Zhejiang, China; these samples group by chronological phase and suggest systematic changes in the rice weed flora, and how rice was cultivated, over time.

tics, provide a guide for the identification of these different forms of cultivation in archaeological phytolith samples, which routinely include forms from rice alongside likely weeds. In addition to studying modern crops and weeds, we have surveyed stands of wild rices, so that we can determine what species co-occur with rice's wild relatives and how this may be distinguished from the weed flora of early cultivated fields. Through this method we should be able to recognize 'pre-domestication cultivation', the very start of the process as well as ancient exploitation of wild rice stands.

Preliminary results indicate that modern phytolith assemblages differ between wild rice habitats and those of cultivated rice, while different cultivation types (e.g. rainfed, lowland flooded, deepwater) also differ. This indicates the potential of phytoliths to distinguish different modes of rice use (wild or cultivation) and forms of cultivation archaeologically. We are now studying phytolith samples as well as archaeological seeds from a series of archaeological sites in the Lower Yangzte to trace the evolution of rice agriculture, these sites include Tianluoshan (5000–4300 BC), Majiabang (4500–4000 BC), Caoxieshan (4000–3800 BC), Xiaodouli (3800–3300 BC), Yujiashan (3300–2000 BC), Maoshan (3300–2000 BC), as well as some sites from other parts of China. Our preliminary results indicate a story of changing agricultural practices in the weeds (**Fig. 6**). This includes an increase in weed diversity overall, but a decline in deeper water perennials. The latter suggests improved techniques of tillage and control of water depth over time. Some key weeds of rice, such as the sedges of genus *Fimbristylis* which are very widespread as weeds today, appear in sites later than Tianluoshan.

Chinese rice domestication and the spread of rice in Asia

Rice was a wild wetland species which was brought under human management in artificial wetlands in Neolithic China. The evidence from Tianluoshan indicates that domestication process for rice was still underway at 4600 BC, but it had crossed the tipping point when domesticated forms outnumbered wild forms in the local populations. It is possible that the process began as much as 2,000 years earlier, but adequate archaeobotanical evidence is still missing. Evidence from later sites, such as Caoxieshan, indicate that changes slowed by 3800 BC, which can be taken to mark the end of a domestication episode that may have lasted nearly 3,000 years in all. Sites of a similar age elsewhere in China, such as the sites of Bashidang (Hunan province) on the Middle Yangtze or Jiahu (Henan province) on the Huai River, provide evidence for large scale rice use and probable early cultivation between 7000 and 6000 BC. Detailed study of spikelet bases that track morphological change or associated weed flora and phytolith assemblages are not yet available, but a parallel local process of rice domestication can be envisioned in these regions. The methods of sampling and analysis that have been developed through our work in the Lower Yangtze can be employed to test the hypotheses of multiple rice domestication processes and to enable comparisons.

Ultimately the rice cultivation of these regions fuelled the expansion of agricultural populations in much of eastern Asia.[1] Paddy-field systems are known later to have appeared in Shandong province (eastern China) by 2500 BC, South Korea by 1000 BC, and Yayoi period Japan from 800 BC, and upland rice, cultivated on higher rainfall in uplands without irrigation systems also developed and spread southwards to Southeast Asia by c.2000 BC. We are also exploring the development of rice cultivation in Thailand through the work of a PhD student (Castillo).

A revised scenario for early Indian rice

While the early rice in China was ancestral to the subspecies *japonica,* another major subspecies of rice, *indica* has roots in India, which remain archaeologically somewhat mysterious. Although rice use is established by c.6500 BC at the site of Lahuradewa in the middle Ganges Valley, later evidence, from c.2500 BC, is clear that rice was an established crop, and for some sites the only crop in this region.[3] Recent genetic evidence suggests that *indica* origins required hybridization from introduced East Asian rice strains (of *japonica*) and native wild rices of South Asia.[4] One likely explanation is that rice farmers in India or Pakistan received through down-the-line trade, rice from the another region (China) that already had domestication genes, and noting the differences in the plants produced, chose to create hybrids with their local inferior varieties. While modern genetics can highlight the complex history of these species, archaeological evidence provides a framework of space and time in which this hybridization might have occurred. We hypothesize that in Pakistan and Northwest India this took place c.1900 BC or shortly thereafter, since at this time several crops of Chinese origin (common millet, hemp, peaches, apricot) and harvesting tools that look like those earlier in China, first appear. After this period rice cultivation became larger scale and more widespread across northern India.[1,3]

The available evidence from India suggests that early rice in the Ganges valley was dry-cropped, that is based on monsoon rainfall and some natural riverbank flooding. This is inferred from co-occurring weed species found on archaeological sites with rice. Evidence from some later sites suggests wet-field systems were used by 1000 BC. Once such labour intensive but highly productive systems were established, rice cultivation spread widely in India, including southwards to Tamil Nadu and beyond to Sri Lanka. We are also investigating this process, as more intensive irrigated rice was developed in India and spread to Sri Lanka through archaeobotanical research on sites in Orissa, such as Golbai Sassan, that date between 2000 and 1000 BC, and through archaeobotanical research in northern Sri Lanka at the site of Mantai, where rice is present from the earliest levels of c.200 BC. This South Asian archaeobotanical research is the focus of a PhD Student (Kingwell-Banham).

The relevance of ancient rice agriculture to global change

The expansion of ancient rice agriculture is likely to have had an effect on past methane levels. Rice paddies, as artificial tropical wetlands, produce methane. Wet and irrigated field systems of rice may produce higher yields of grain but they also produce more methane than dry or rain fed rice fields as well as greater crop yields, so the expansion of paddy farming should contribute to higher methane levels. Using patterns created by weed assemblages from a variety of rice arable systems it is possible to interpret different types of field system in archaeobotanical samples. Taken together with the total archaeological record for rice, and using recent GIS techniques we have modelled the spread of rice and areas under wet rice agriculture over time in order to estimate the likely production of methane from rice farming over past millennia.[5] In this way our archaeobotanical research on early rice agriculture can also contribute to on-going climate science debates about human contributions to greenhouse gases over the long-term. Archaeology, as a record of past human activity, subsistence successes and failures, has insights to offer to very current discussions of the impact of human land-use.

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