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# Transitions in Productivity: Rice Intensification from Domestication to Urbanisation

*Dorian Q. Fuller*

## Abstract

Archaeobotanical research in East and Southeast Asia provides evidence for transitions between lower and higher productivity forms of rice. These shifts in productivity are argued to help explain patterns in the domestication process and the rise of urban societies in these regions. The domestication process, which is now documented as having taken a few millennia, and coming to an end between 6700 and 5900 BP, involved several well documented changes, all of which served to increase the yield of rice harvests by an estimated 366 per cent; this increase provides an in-built pull factor for domestication. Once domesticated, rice diversified into higher productivity, labour-demanding wet rice and lower-yield dry rice. While wet rice in the Lower Yangtze region of China provided a basis for increasing population density and social hierarchy, it was the development of less productive and less demanding dry rice that helped to propel the migrations of farmers and the spread of rice agriculture across South China and Southeast Asia. Later intensification in Southeast Asia, a shift back to wet rice, was a necessary factor for increasing hierarchy and urbanisation in regions such as Thailand.

**Keywords:** agriculture, archaeobotany, Neolithic, civilisation, China, Southeast Asia

Understanding the development, diversification and spread of agriculture is central not only to our understanding of the processes of human population growth, dispersal and formation of civilisations, but also to reconstructing how past agricultural activities might have impacted regional environments and the global climate, through deforestation and carbon emissions from sources such as methane-generating wet rice (Fuller et al. 2011; Ruddiman et al. 2016). Over the past decade, the archaeobotany laboratory at UCL has made concerted efforts to improve our archaeological evidence for past rice agriculture and also our methods for reconstructing how rice was cultivated across large parts of South Asia, Southeast Asia and China, supported by a sequence of three grants from NERC (Fuller and Weisskopf 2011; Fuller, Weisskopf and Castillo 2016). We have worked on a range of sites and periods, from documenting the rice domestication process, to examining local shifts to rice away from other crops, to instances of intensification of rice production (Figure 1). Our increased evidence for rice and how it was cultivated provides a basis for thinking about how land productivity differed across the rice-growing world over time, and how this in turn related to key social transformations, including Neolithic population growth and episodes of urbanisation.

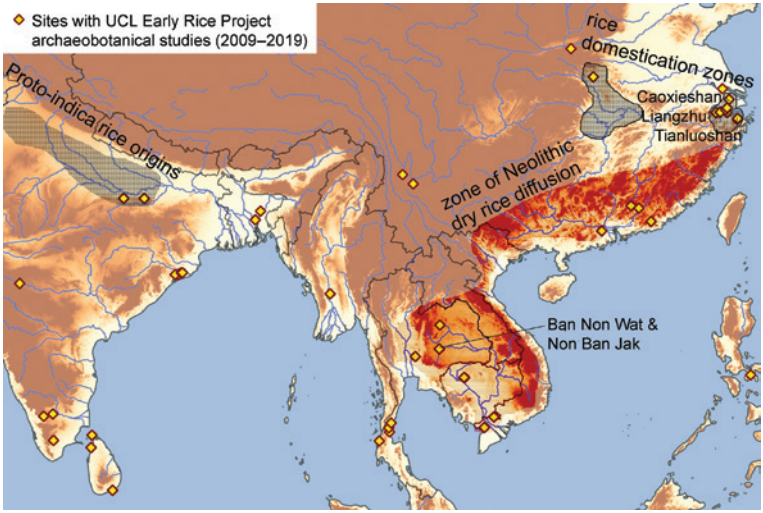


**Figure 1** Map of regions and sites discussed in the text. (Image credit: Dorian Q. Fuller)

Rice has featured in the agriculture of South, East and Southeast Asia since prehistoric times and has supported many early urban cultures from the Yangtze valley of China through all the major rivers of Southeast Asia, as well as much of India and Sri Lanka. Highly productive wet rice has traditionally supported the highest population densities (see, for example, Scott 2009), while low-intensity dry rice also persists in areas of Asia with lower population densities and lower labour requirements. This highlights the significance of the ecological spectrum between the wet and dry ecologies of rice cultivation, and transitions in both directions have been a feature of the history of rice cultivation in southern China, Southeast Asia and the Indian subcontinent which we are now better able to outline (Kingwell-Banham 2019; Qin and Fuller 2019). In the present paper I explore how shifts in rice ecology can be interpreted in terms of shifts in productivity, from the domestication process through to the intensification and urbanisation processes. I will make the case that, based on current evidence, urbanisation processes in southern China, Southeast Asia and much of India, only took place once higher-yield, wet rice production became common.

## Domestication and the pull of rice productivity

The earliest archaeological evidence for rice farming comes from the Yangtze basin in China, where domesticated rice is present in the middle Yangtze by perhaps 8000 BP (Deng et al. 2015). In the Lower Yangtze, domesticated rice starts to outnumber morphologically wild rice *c.*6700 BP (Fuller and Qin 2009; Fuller et al. 2016). Recent work has continued to push the beginnings of rice cultivation and domestication processes earlier, for instance back to 9000–11,000 BP (see, for example, Ma et al. 2016; Qiu et al. 2019; He et al. 2020), and by extrapolating backwards from the rate of evolution in domestication traits, the very beginnings of these processes might actually stretch back to *c.*13,000 BP (Allaby et al. 2017). This means that the evolution of domesticated rice and rice agriculture was a very long process, and the first half of this process is still poorly known.

The distribution of archaeobotanical finds of early rice clusters in two regions, likely two distinct domestication centres in China,

is also supported by distinct material culture traditions and early forms of field systems (Fuller and Qin 2009; Makibayashi 2014). The domestication of rice involved a pretty significant transformation from what was a perennial wetland grass with fairly low grain productivity (*Oryza rufipogon*) (Morishima and Barbier 1990; Fuller and Qin 2009) to a facultative annual with high investment in seed production and self-pollination. This is in addition to the changes that are characteristic of all cereal domestications, such as the loss of natural seed dispersal (shattering), even ripening, loss of dormancy, increase in erect growth and apical dominance and an increase in grain size (Fuller 2007; Ishikawa, Castillo and Fuller 2020). It has been argued that the increase in grain production was driven initially by harnessing in-built stress responses of wild rice, namely a response to apparent drought, which would have triggered increased investment in grains instead of shoots and leaves. The potential archaeobotanical indictor for this came in the form of a phytolith index indicative of water availability of all grasses in rice assemblages (the fixed: sensitive index). This shifted markedly towards drier conditions at Caoxieshan, near Suzhou (*c.*5900 BP), the first archaeological site with small field systems, in contrast to the earlier very wet ratio recorded from the site of Tianluoshan (7000–6400 BP) that fits with wild rice ecologies (Weisskopf et al. 2015; Fuller et al. 2016).

I would conjecture that initially increases in grain productivity resulted from phenotypic plasticity in ancestral wild rice, which responded to environmental conditions. This subsequently became fixed by genetics, a process called genetic assimilation by biologists interested in plasticity (see, for example, Pigliucci and Murren 2003; Sultan 2015, 146; Piperno 2017). Similar processes may have played a role in many instances of the initial appearance of plant domestication traits before they became genetically fixed, although such a process implies an even slower evolution of domesticated genomes than a simple genes-only 'conventional' model of evolution.

What I would like to consider here, however, are the ways in which the appearance and gradual fixation of domestication traits in rice created an inherent momentum in the domestication process, in as much as it pulled early cultivators towards ever more economic reliance on rice and away from mixed foraging economies. Archaeologists often

argue about why domestication came about and debate the prime movers that caused its beginning, whether these were climate change, population pressure or social competition (see, for example, Hayden 1990; Bar-Yosef 2011; Zeder 2017). All these are potential motivations from outside the domestication process, but what if the coevolutionary process itself has an inherent directionality? While one or more of these factors could play a role in encouraging foragers to experiment with cultivating wild plants and to shift more effort to such cultivars and away from wild resources, the long duration of domestication (two to four thousand years, at least) means that any single climatic event, population boom or social system upheaval is likely to have undergone change more than once during this duration, making a single push factor behind the process less plausible. Instead, multiple factors interacting, including changes inherent to the process, must be considered (Fuller et al. 2016; Zeder 2017). One of these inherent pull factors is an increasing rate of return per unit of land cultivated and unit of labour expended that result from the plant evolving domestication traits.

Wild rice and domesticated rice differ in numerous traits (Figure 2). Recent years have provided increasing evidence from genetics of how rice crops differ from their wild relatives in terms of traits that have a very specific effect on the yield of grains that people can harvest (Ishikawa et al. 2020). In Table 1, I have collected some of those changes in terms of the mean estimates of yield components of the wild versus domesticated type. What will be noted is that various genetic changes have increased yield by factors ranging from 24 to 133 per cent. The lower end of this is represented by grain size increase, a factor which is inherent in all grain crop domestications but which is controlled by numerous interacting genes (Fuller and Allaby 2009); we can still estimate this effect from a comparative study of wild and domesticated rice (Morishima et al. 1961). At the upper end of the genetic changes is the estimate of grains per panicle, as in wild rice many grains fail to mature at all and there are fewer of them, as they are more widely spaced. Two key domestication traits, controlled by a single mutation each, include a shift to a compact panicle (Ishii et al. 2013), which on its own can increase grains harvested, as opposed to being dropped, by around 50 per cent, and a shift to compact and erect growth, which also increases the number of grain-bearing branches per plant by around

100 per cent. Before rice was domesticated, in terms of losing its natural seed dispersal, wild harvests would have included many unfilled or immature grains, while the transition to non-shattering allowed all these grains to stay on the plant until harvest, an estimated boost to returns of around 50 per cent. While all these traits evolved gradually

**Figure 2** A comparison of wild rice (left) and domesticated rice (right). In the top row is a comparison of the spreading habit and panicle of wild rice with the erect growth of the crop. In the second row, basket harvest experiments of wild rice can be contrasted with traditional sickle harvesting to the right. The bottom row compares the yield from a few minutes of basket harvesting, including an immature example of wild rice, versus the pump, dense panicle of domesticated rice. (Image credit: Dr Rabi Mohanty and Dorian Q. Fuller)

across the rice population and may have evolved at various times and rates, their cumulative effect would have increased the return per rice plant by around 360 per cent. In other words, the domestication process itself had a snowball effect of increasing the utility and attractiveness of the crop, a feature that may well have encouraged continued effort. One attempt to estimate the foraging return rates on wild rice produced the meagre estimate of around 90 kcal per hour of work (Lu 2006), and while that may be a low-end estimated, the evolution of domestication would have increased this substantially (to at least 330 kcal/hr).

For societies that are dedicated to cultivation, return rates per hour of work are probably less important than returns per unit of land. Therefore, a comparison of estimate yields (per hectare) of early cultivated rice and gathered wild rice is provided (Table 1), based purely on the difference brought about by morphological domestication (and

**Table 1** Estimates of yield improvement from various domestication traits (genetic changes).

| Domestication trait | Wild type yield | Improved domestic type yield | Percentage increase | Source |
|---|---|---|---|---|
| Closed panicle | 20% | 30% | 50 | Ishii et al. 2013 |
| Seed weight (grams) [i.e. grain size] | 0.0188 | 0.0232 | 24.4 | Morishima et al. 1961 |
| Grains/panicle | 47.5 | 110.6 | 133 | Morishima et al. 1961 |
| Immature to mature harvest (before non-shattering/even ripening) | 60% | 90% | 50 | Fuller 2007 |
| Compact erect growth (grains per plant in grams) | 20 | 42 | 110 | Tan et al. 2008 |
| Yield kcal/hour (wild harvest experiments) | 90 | | | Lu 2006 |
| Yield kcal/hour with domestication | | *330* | *366.2* | Total estimated improvement from above |
| Yield kg/ha | 232 (218–246) | 850 (800–900) | *(366)* | Based on Qin & Fuller 2019 |

assuming human labour inputs were equivalent). Indeed, the transition from hunting and gathering to agriculture is in part a transition in values: a change to valuing getting more from the land over an efficient use of time (Bar-Yosef 1998; Fuller 2007) – after all, cultivators have invested months in preparing land and raising crops. As many have noted, the rise of agriculture encouraged new systems of land tenure or ownership (Bowles and Choi 2013; Gallagher, Shennan and Thomas 2015) – although there is much to debate about how precisely that worked (Graeber and Wengrow 2018; Bogaard et al. 2019). It is plausibly the case that it is only with long-term perennial tree crops, managed over many years, that land ownership as we think of it today emerged (cf. Fuller and Stevens 2019). Bogaard, Fochesato and Bowles (2019) argue that inequality was specifically linked to the emergence of land-limited, rather than labour-intensive, agriculture. I return to this point below and question whether such a pattern is relevant to rice-growing Asia. In any case, for thinking about the scale, growth and spread of societies with farming economies, the yield per units of farmland is important, as it determined potential population sizes, and the potential for surpluses to support non-subsistence specialists.

## Rainfed rice and more rapid dispersal

After domestication was completed, subsequent farming was focused on well-irrigated rice in the Lower Yangtze and the Middle Yangtze (Qin and Fuller 2009; Nasu et al. 2012; Weisskopf et al. 2015). Rice that dispersed rapidly to northern China around 6,000 years ago was also presumably irrigated, even if it had productivity issues under temperate conditions (Fuller et al. 2016). By contrast, there was a significant delay before rice spread south, with the earliest dates from Taiwan at 5000–4500 BP (Tsang et al. 2017), the earliest dates from Guangdong (the Pearl River delta) after 4600 BP (Yang et al. 2018) and the earliest finds of rice in Southeast Asia (Thailand and Vietnam) dating from between 4500 BP and 4000 BP (Castillo 2017; Qin and Fuller 2019). This indicates a rapid dispersal across some 15,000 to 16,000 km between the Pearl River and Southern Thailand in a few centuries at most, as opposed to the millennia (two thousand years or more)

that it took to spread from the Middle Yangtze to the Pearl River, a distance of only around 700 km.

One hypothesis for the slow spread of rice farming across the south of China is that wet systems of cultivation were labour intensive and precluded by simpler social systems in the south. In other words, it was either the lack of required labour or an unwillingness to toil that slowed the adoption of rice. So far there is little evidence with which to test this, but increasing data from Guangdong and Fujian indicates that rice and millets (always a dry crop) spread together, and weed evidence when available shows the presence of dry agriculture (Deng et al. 2015; Qin and Fuller 2019). An additional factor is that higher sea levels during the mid-Holocene meant that there was less low-lying land suitable for wet rice fields until after 3000 BP, when there was a large expansion of irrigated rice fields during the local Bronze Age (Ma et al. 2020). Available data from Thailand indicates that the earliest rice was genetically *japonica* (from China) and ecologies there were rainfed (Castillo 2017; D'Alpoim Guedes et al. 2020). Nevertheless, it is the case that the Neolithic dispersal of rice from southern China to throughout Southeast Asia took place rapidly and without the presence of wet rice paddies.

To understand this, we need to take into account the inherent difference in the productive potential of dry versus wet rice systems and their demographic effects. While it is not possible to directly recover the range of rice productivity in the past, the range of potential productivity under traditional production methods is clear from ethnographic and historical data (Figure 3). Dry rice grown in swiddens in Borneo, for example, has reported yield as low as 229 kg/ha, with the highest yields just over 1,000 kg (Barton et al. 2012). Traditional yields in India up to the 1950s rarely exceeded 1,000 kg/ha (see, for example, Heston 1973; Qin and Fuller 2019), while in Sumatra yields could be up to 1,500 kg/ha (Sherman 1990). By contrast, while wet rice yields might have been as low as 1,000 kg/ha during the Han Dynasty (Ellis and Wang 1997), most were typically over 2,000 kg/ha in nineteenth-century Japan or Southeast Asia (Bray 1986). Taking into account these yields and the requirements for fallow with rainfed (dry) rice, it can be estimated that the amount of cultivated rice lands required to support 50 people was around 17 ha for dry rice and just 8 ha for wet rice (Figure 3B).

This means that to support a typical Neolithic Yangtze village of 3–4 hectares, just 24–32 hectares needed to be cultivated, in contrast to the 53–71 hectares that would have been needed for rainfed rice. This difference also limited the potential population and size of any self-sustaining settlement, or, in other words, it affected the carrying capacity of rice agriculture. With early wet rice and yields of perhaps 1.5 tonnes/ha, we can expect to support populations up to about 14,000 people – perhaps the modest size of the earliest urban centres, such as the 280 hectare city of Liangzhu (5300–4300 BP) in the Lower Yangtze region (Renfrew and Liu 2018; Qin and Fuller 2019). By contrast, dry rice is unlikely to be able to support communities of more than 2,500–3,000 people.

While it is likely the case that most ancient societies operated below ecological carrying capacity (Sahlins 1972), it is surely the case that as community sizes grew, the main release for population pressure was outward migration. This is the principle of demic diffusion; long discussed and quite well-evidenced for much of Neolithic Europe (see, for example, Shennan 2018). With the higher productivity of wet rice, populations could be packed into the landscape at much higher density; what is more, wet rice required higher labour input, so those higher population densities could be put to work. In contrast, dry rice farming (and also millet farming) could only support more modest communities and population growth would outstrip this production more quickly, perhaps four or five times more quickly. This means that dry

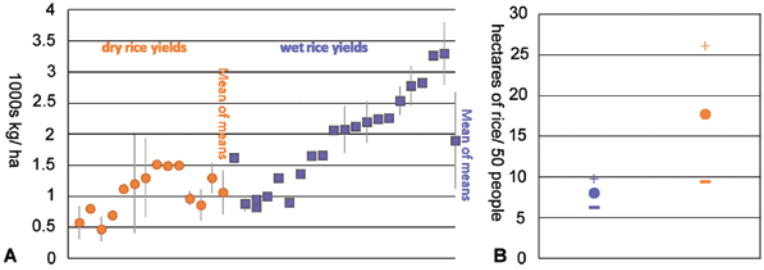


**Figure 3** Contrasting rice yields and land area needs for wet and dry rice. A) Reported rice yields, including standard deviation where available from traditional and historical sources, contrasting dry and wet systems. B) Estimated land areas needed to support 50 people under early production systems of wet versus dry rice. (Image credit: Qin and Fuller 2019)

rice farming communities are much more like to have frequent fission and emigration events. It is the less productive dry farming that fuelled the demic expansion of Neolithic cereal agriculture through southern China and Southeast Asia, especially between 5000 and 4000 BP.

## Intensive wet rice and urbanisation

Over the long term and in the large geographies of rice-growing Asia there are multiple trajectories of agricultural change, both towards and away from wet rice. Wet rice was much more productive, but also consumed more labour. Thus a transition towards less-intensive dry rice farming appears to have preceded the Neolithic expansion throughout Southeast Asia and to have underpinned early village economies in most of that region. In contrast, in the Yangtze basin where wet rice was established already during the domestication process, increasing yields could be guaranteed through labour investment and the slow transformation of more low-lying wild lands into rice fields. This allowed for population densities to increase, packing more people into the landscape instead of spreading out to other areas. This packing in of people and the intensification of wet rice production through agricultural labour are well-documented processes for the historical period in many parts of China (Bray 1986; Ellis and Wang 1997). However, it seems to have been part of the Neolithic story in the Yangtze basin as well, allowing for an Indigenous transformation of Neolithic village economies into a hierarchical society focused around the elite city centre of Liangzhu that emerged around 5300 BP (Qin 2013; Renfrew and Liu 2018). In other words, the agricultural basis for urbanisation was in-built from the very beginnings of the domestication of rice.

By contrast, the transition to wet rice agriculture was a secondary development in Southeast Asia. In Northeast Thailand, thanks to archaeobotanical sampling at the sites of Ban Non Wat and Non Ban Jak, we have a continuous archaeological sequence of rice cultivation from *c.*3000 BP to 1300 BP. Archaeobotanical research on these sites at UCL by Cristina Castillo demonstrated a major shift from only dry ecology weeds before 100 BCE (2100 BP) to an increase in wetland weeds post that date, as well as the disappearance of most dry land indicators by

the third century (1800 BP) (Castillo et al. 2018). Phytolith work by Alison Weisskopf also demonstrated a high index of wetness for Non Ban Jak at the end of this sequence (Fuller et al. 2016). This shift towards irrigation coincides with regional palaeoclimate evidence for decreasing rainfall. In other words, rice fields got wetter as the climate became drier and cultural practices compensated for climatic change (Castillo et al. 2018). Rather than being abandoned, sites persisted and increased in size and number: the population was able to grow denser because of labour-intensive investment in wet rice.

This Iron Age period in Northeast Thailand also provides increasing evidence for growing social complexity. In other words, wet rice provided the basis for increases in social hierarchy and the growth towards urbanism in Thailand. In terms of thinking about land and labour, mainland Southeast Asia followed a trajectory of land-limited agriculture of the dry-rice Neolithic to labour-limited agriculture that greatly increased the value of land and its productivity with the advent of wet-rice farming in the Iron Age. The historical patterns of most of Southeast Asia were based on the availability of large populations that provided labour for highly productive wet rice, with less productive forms of agriculture in the hills providing an anarchic refuge from state power (Scott 2009). Although it is beyond the scope of this article, we see similar transitions to more wet rice production linked to increasing population density, urbanisation and social complexity in many parts of ancient India (see Shaw et al. 2007; Fuller and Qin 2009; Kingwell-Banham 2019).

## An alternative rice route to civilisation?

Recent advances in the archaeobotany of early rice agriculture have greatly improved our appreciation of both the diversity in cultivation systems across Asia and the similarities of response. Domestication processes themselves likely had in-built momentum, in part because of the increasing productivity of rice that accrued through genetic changes, which locked growing communities into reliance on this cereal. Once established, rice agriculture went in two directions – towards less intensive, but more geographically expansive systems, suited to smaller scale

village societies, or to intensive systems that packed populations into a region through increased labour, and so increased the value of each unit of land. Among the responses that wet-rice agriculture allowed was the creation of dense populations that included a large proportion of hard-working rice farmers that supported urbanisation and the emergence of elite culture, and we can see that this happened numerous times across China, Southeast Asia and India.

The pathways towards rice-based civilisation, however, contrast with the historical experience of the Near East and Europe. The proposed evolutionary trajectory from labour-limited to land-limited agriculture has evidential support and explanatory value in the context of Mesopotamia and parts of Europe (Bogaard et al. 2019), but it appears at odds with the long-term experience of rice-growing Asia. Instead, what the long-term trajectories of rice-based economies indicate is that not all domesticates nor all agricultural systems were equivalent. It is the need to reveal this diversity of past human experiences with regards to agricultural systems, land values and social hierarchy that calls for the systematic deployment of archaeobotanical research programmes in more regions and periods.

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## Conflict of interests

The author declares no conflict of interests with this work.

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