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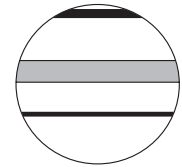
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The contribution of rice agriculture and livestock pastoralism to prehistoric methane levels: An archaeological assessment

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Abstract

We review the origins and dispersal of rice in Asia based on a data base of 443 archaeobotanical reports. Evidence is considered in terms of quality, and especially whether there are data indicating the mode of cultivation, in flooded ('paddy' or 'wet') or non-flooded ('dry') fields. At present it appears that early rice cultivation in the Yangtze region and southern China was based on wet, paddy-field systems from early on, before 4000 BC, whereas early rice in northern India and Thailand was predominantly dry rice at 2000 BC, with a transition to flooded rice documented for India at *c.* 1000 BC. On the basis of these data we have developed a GIS spatial model of the spread of rice and the growth of land area under paddy rice. This is then compared with a review of the spread of ungulate livestock (cattle, water buffalo, sheep, goat) throughout the Old World. After the initial dispersal through Europe and around the Mediterranean (7000–4000 BC), the major period of livestock expansion is after 3000 BC, into the Sub-Saharan savannas, through monsoonal India and into central China. Further expansion, to southern Africa and Southeast Asia dates mostly after 1000 BC. Based on these two data sets we provide a quantitative model of the land area under irrigated rice, and its likely methane output, through the mid to late Holocene, for comparison to a more preliminary estimate of the expansion of methane-producing livestock. Both data sets are congruent with an anthropogenic source of later Holocene methane after 3000 BC, although it may be that increase in methane input from livestock was most significant in the 3000–1000 BC period, whereas rice paddies become an increasingly significant source especially after 2000 BC.

Introduction

Studies of palaeoclimatic proxies from the Holocene, in comparison with previous interglacials, suggests that overall climate and greenhouse gases are out of synchronization with orbital and solar insolation forcing mechanisms. Derived from such observations is the hypothesis that anthropogenic greenhouse gas elevation began in the middle Holocene (Ruddiman, 2003, 2007; Ruddiman and Thomson, 2001; Ruddiman et al., 2008). Since paddy fields are a major non-industrial source of methane (Aselman and Cruzten, 1989; Neue, 1993), it is suggested that one of the major contributing factors to a rise in global methane levels from after 3000 BC was the development and expansion of wet-rice agriculture (Li et al., 2009; Ruddiman et al., 2008). This paper contributes to a test of this hypothesis on the basis of archaeological evidence for rice cultivation in Asia.

Ruddiman and Thomson (2001) relate possible methane emissions from rice in Asia to population growth. They discuss the implications of different levels of farming efficiency for the harvested area of paddy rice, arguing that per capita land use must have decreased over time, given methane emissions and population numbers. Although there are some recent attempts to estimate farming efficiency from palaeosol and weed seed density data (Zheng et al., 2009), deriving reliable estimates, especially for

larger areas, is problematic. Following Boserup (1965), it might be argued that farming efficiency is not determined by technological mastery but rather by population pressure. Indeed, Ruddiman and Ellis (2009) explore the consequences of a rise in farming efficiency over time and show how this leads to higher estimates of cultivation and deforestation in earlier periods.

In another contribution, Ruddiman et al. (2008) provide quantitative data for the increase in methane emissions by presenting the number of Chinese archaeological sites with cultivated rice over time. A bias for early rice sites is evident, making it possible

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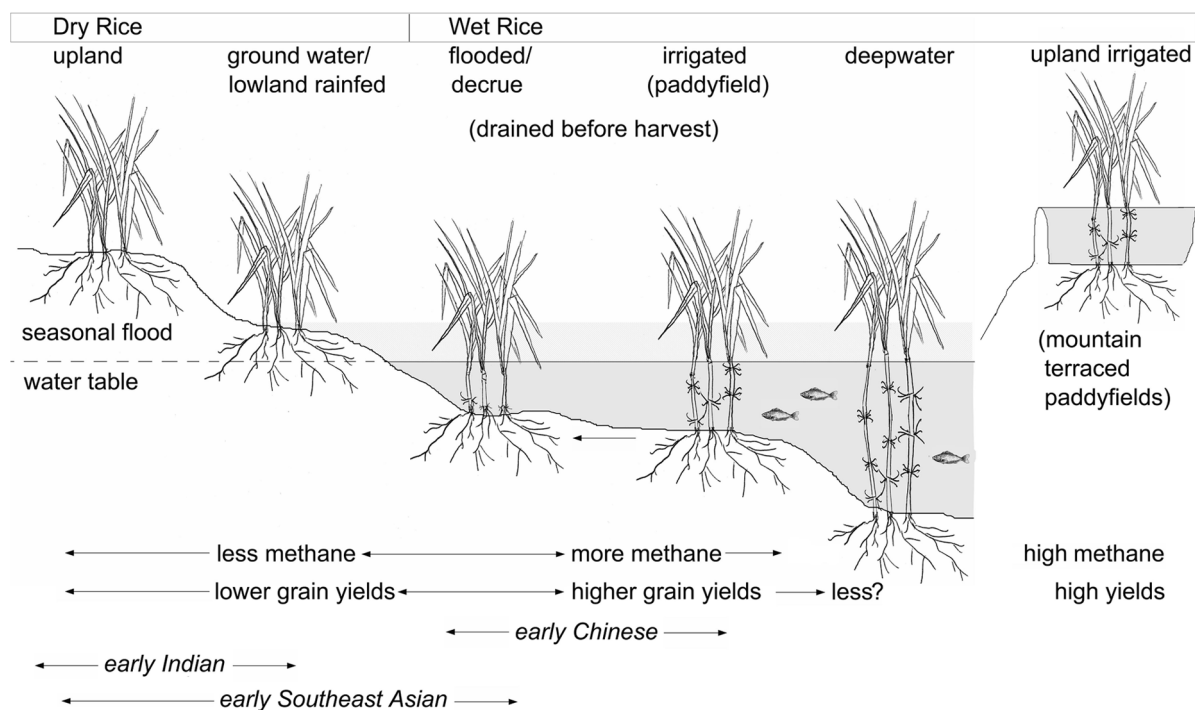Email: d.fuller@ucl.ac.uk

Figure 1. Schematic diagram contrasting the major variations in rice cultivation systems, including dry and wet field types. The diagram represents schematically variation the extent of standing water and rainfall through the rice growth cycle. Indicated across the bottom of the diagram are expected methane and grain output trends. In addition the earliest regimes inferred for various regions are indicated (based on discussions in Castillo and Fuller, 2010; Fuller and Qin, 2009; and this article)

to generate plausible scenarios for the earliest arrival of rice in each region, but making it difficult to trace the expansion of rice area over time. Ruddiman et al. (2008) show that the start of anthropogenic methane emissions coincides with a period of strong growth in the number of Chinese archaeological rice-growing sites. However, before the apparent start of anthropogenic methane emissions around 3000 BC, a considerable number of rice sites are recorded.

To fully flesh out a plausible scenario of the start of rice paddy methane emissions and explore the compatibility with the scenario for anthropogenic methane emissions, we compiled an updated and expanded archaeobotanical data base, including sites from outside of China, and where available additional proxy evidence for the conditions of cultivation, whether wet or dry. We provide a spatially explicit account of the increase of the harvested area of rice. Using these data, we model the first 'wave' of the spread of rice cultivation across Asia. We then present a scenario for the subsequent expansion of the harvested area of rice, based on a simple linear growth model. Lastly, we then consider our modelled results alongside a first synthesis of the potential adjunct contribution of the spread of ungulate livestock such as cattle.

Rice productivity in terms of output per unit of land is heavily dependent on the water regime. Rice fields can be flooded (we refer to this as 'paddy rice', 'wet rice'), or non-flooded ('dry' rice, sometimes referred to as 'upland rice'). Flooded fields are typically bunded, and water can be supplied through irrigation, or by retaining water from rainfall and lateral water flows. Figure 1 illustrates schematically the spectrum of rice cultivation regimes, and the general tendency for there to be more methane output with deeper water systems (Neue et al., 1997), although the floating varieties of rice in the deepest water may produce less

methane (Bouwman, 1991: 66; cf. Neue, 1993: 470). While wetter rice systems produce more methane, it is also clear that the timing of flooding and drying, fertilizer inputs and genetic strain of rice all contribute additional variation (Bouwman, 1991; Neue et al., 1997). The most productive rice crops are grown in paddy fields, which are irrigated and retain standing water for much of the growing season. Before the introduction of modern varieties, these more productive crops are also usually slow-maturing crops taking 6 to 9 months from planting to harvesting. Irrigated rices require a substantial capital labour investment in the creation and maintenance of field systems and irrigation. Nitrogenous manufactured and organic fertilizers, including the burning of previous season's rice stubble, contribute to higher yields and increasing methane outputs (Bouwman, 1991). Wet-rice systems have the added potential of efficiently producing protein through the stocking of these fields with fish, usually carp (*Cyprinus, Carassius*), a practice developed in East Asia by 2500 years ago at the latest (Nakajima et al., 2010a, b). Higher rice yields are also provided by systems of transplanting, where rice is sprouted in a nursery bed and then young plants are separated and replanted by hand in an already flooded field. Such systems greatly reduce competition from weeds. Faster maturing rice varieties may be expedient where water availability is limited or other crops require land and labour (e.g. Ho, 1956). Where rainfall is high enough, usually >800 mm (Jacquot and Courtois, 1987: 16), rice may be sown on non-flooded soils and raised as a dry crop, like other cereals. Such dry/upland rices may also be sown as part of the crop-rotation in swidden agricultural systems, normally in the first stage after forests have been cleared and burned (Jacquot and Courtois, 1987; Spencer, 1966). These dry rice systems are not expected to produce much methane, and nothing in excess of other dry-crops such as millets or wheat (Bouwman, 1991). It is therefore critical

to develop better estimates of which archaeological rice finds represent wet as opposed to dry rice.

Another potential limitation of these earlier assessments is that blame is placed entirely on rice cultivation whereas other anthropogenic sources, such as the spread of ruminant stock-keeping (cattle, buffalo, sheep, goat) is not considered. Livestock herding might also have contributed to methane production in the past, and we return, below, to an archaeological case for a livestock component to Holocene methane levels.

A critical data base to refine the archaeobotany of Asian rice

The present study starts from a data base of rice archaeology, designed with archaeological questions in mind, to take full advantage of detailed and often quantifiable variation in the data for rice. Previous reviews have been less critical of the relative quality of reported rice data, i.e. what is demonstrated versus what is implicitly assumed. Ruddiman et al. (2008) provided a simple tally of Chinese archaeological rice reports over time, and Li et al. (2009) attempted a descriptive synthesis on rice throughout Asia. However, imprecision in where rice was cultivated/domesticated or gathered wild, the importance of other crops, and ambiguities in chronological evidence can be noted in these papers. Where domesticated rice was present, was it cultivated in wet or dry systems? Where rice was cultivated to what extent can it be inferred to have been the dominant basis of subsistence, as opposed to other crops such as dry-grown millets?

As stressed in recent discussions of rice domestication (e.g. Fuller et al., 2007, 2008), any find of rice (husk temper impressions in pottery, leaf phytolith, husk phytolith, charred grain), has often been assumed to represent rice agriculture, whereas the likelihood of hunter-gatherer collecting of wild rice, and various stages in the gradual development of rice agriculture has been overlooked. One presumes that the tropical wetlands to which the wild progenitors of rice (especially *Oryza rufipogon*) is native, would produce methane, so the question must be when and where did rice cultivation expand upon and exceed the land area that was naturally under wild rice or other natural wetland. And what was the balance of the spread of wet rice versus dry rice systems? In principle these are entirely tractable archaeobotanical questions, although we are still in an early stage in the development of rice archaeobotany and much of the existing data are of more limited value in addressing these issues. For this reason we set out to establish a baseline data base on the archaeology of rice, which assess the quality of the data (Fuller et al., 2010).

Our data base (Table S1, available online) summarizes archaeobotanical evidence for 385 sites including 443 individual site/phase data entries, with a focus on rice in Asia that pre-dates AD 1 (expanded from the 386 entries of Fuller et al., 2010). For the tabulated evidence five aspects of the quality of the evidence are scored. This includes the quality of archaeobotanical sampling and reporting, ranked on a four-point scale of interpretative utility (based on Fuller and Weber, 2005). Dating evidence is also indicated, ranging from the most reliable dates, direct Accelerator Mass Spectrometry (AMS) dates on rice remains, to associated radiocarbon dates on other organics, to dates inferred from depositional context and associated artefacts. Whether or not there was explicit consideration of evidence for cultivation or domestication is indicated. In those rare instances where weed flora data are available, or where field systems are preserved, it is also possible

to infer whether rice was cultivated in wet or dry systems. Although further methodological development of this approach is needed some provisional assessments are provided based on lines of evidence developed in Fuller and Qin (2009). Unfortunately, most sites lack any evidence for inferring the nature of cultivation systems or domestication, and even less common are sites where explicit reporting of morphological details allows an assessment of morphological domestication status. This means that the beginnings of rice agriculture remain poorly constrained chronologically between the early and mid Holocene (Figure 2A), and the number of starts to cultivation is unclear (see Fuller, 2006; Fuller et al., 2008, 2010). In later periods as rice cultivation became more widespread and spread to new regions, the archaeobotanical evidence is more extensive, and provides the basis for inferring the major dispersal events in the spread of the rice crop (Figure 2B).

Rice origins and spread in East Asia

Rice is widely accepted as a crop native to southern China (e.g. Fuller, 2007; Vaughan et al., 2008). In the tropics, rice germination from seeds falling to the ground may have been enough to maintain early rice cultivation but in the more temperate regions of north and central China propagation was more likely to have depended on annual seeding by early cultivators (Chang, 1989: 410). Where the dividing line between these regions should be drawn for the early or middle Holocene is, however, unclear. Traditional thought in China has tended to assume early rice domestication (Ho, 1977). Disputed dates for early domesticated rice range in China from *c*. 10 000 to 4000 BC. Recent considerations of evidence for pre-domestication cultivation and wild rice foraging suggest that cultivation was certainly underway by *c*. 6000 BC in both the middle and Lower Yangtze, but that morphological domestication, measured by the dominance of non-shattering rice panicles, was achieved after 4600 BC (Fuller et al., 2008, 2009). Additional evidence for a local domestication process at this time in the Lower Yangtze comes from morphometric data of both grains and phytoliths (Fuller and Qin, 2010; Fuller et al., 2007, 2010; Huang and Zhang, 2000). Early cultivation of rice was a component of broad wild food economy which utilized natural wetland and woodland plants which emerged alongside regional ecological trends towards increasing freshwater wetland and woodlands over the course of the early to mid Holocene (Fuller and Qin, 2010). Despite some evidence for localized management of vegetation there is no evidence for large-scale creation of artificial wetlands for rice cultivation until after domestication, i.e. after 4500 BC (Fuller and Qin, 2009, 2010; see also Qin et al., 2010; Shu et al., 2010).

Rice spread first northwards in China, and later to the south and east (Fuller et al., 2010). By 6000 years ago rice cultivation had moved north of the Yangtze watershed to the middle Yellow River region, with evidence from sites such as Nanjiaokou and somewhat later Xipo (Qin and Fuller, 2009; Weisskopf, 2009; cf. Rosen, 2008). The further spread, through Northeast Asia on the one hand, and up the Yangtze to Sichuan and Yunnan, was delayed until after 2500 BC. Rice has been reported from the end of the Neolithic or early Bronze Age in the Chengdu plain and in Yunnan, i.e. *c*. 2000 BC (An, 1999; Fuller et al., 2010). The nature of cultivation systems in these regions is unconfirmed but is expected to have been focused on wet-field systems. In Korea
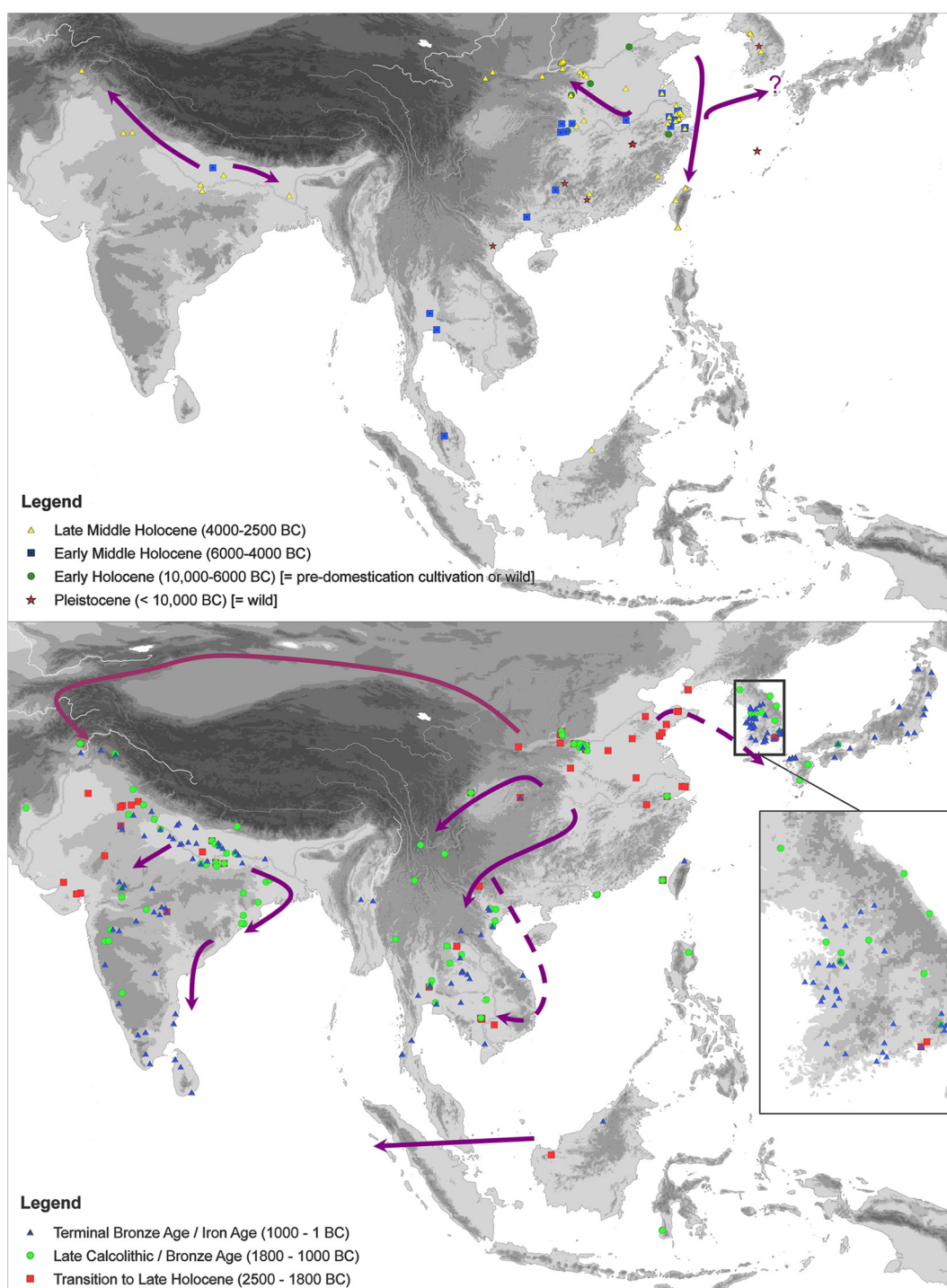
Figure 2. Maps of distribution of rice finds in broad chronological horizons. Arrows indicate major dispersal events, with estimated age of dispersal indicated (after Fuller et al., 2010; updated based on Table S1, available online). Gray shading indicates topography in 300 m intervals. Not explained

securely dated and identified rice is rare and controversial before *c*. 1500–1300 BC (Ahn, 2010). Any rice that was as early as that or earlier than 1500 BC, is likely to have been dry-cropped rice. Dry cropping also has been attributed by some scholars to a few rare finds of rice phytoliths from late Jomon culture contexts in Kyushu, Japan, which may be of similar age (D'Andrea, 1999; Sato, 1996), although in the absence of grains and direct dates, how much before 1000 BC these finds date is unclear (Keally, 2004). Dry-cropped rice in the terminal Jomon of Northern Japan is confirmed by a direct date on a grain from Kazahari at *c*. 800 BC (D'Andrea et al., 1995). The spread of paddy fields is attributed to diffusion in the Bronze Age from China to Mumun, Korea (from 1500 to 1300 BC), and onwards to Japan with

immigrants in the Yayoi period which starts after 900 BC in Kyushu, and is established after 400 BC throughout most of Japan. In both Korea and Japan, preserved palaeosols from paddy-field systems confirm the cultivation regime (Takahashi, 2009; Tanaka et al., 2010), although dry cropping was also carried out, and millets recur alongside rice (see Ahn, 2010; Crawford and Lee, 2003).

Rice agriculture origins in Southeast Asia

It is generally accepted that domesticated rice spread through Southeast Asia from origins in China, and migration models are

usually proposed. The Higham model from mainland Southeast Asia traces early farmers from southern China (Yunnan, Guangxi), with a dispersal working down river valleys (Higham, 2002a, b), whereas in Insular Southeast Asia, Bellwood (2007) postulates a spread of rice farming with Austronesian speakers from mainland China to Taiwan and parts of the Philippines and island Southeast Asia. Andarayan in the north of the Philippines perhaps illustrates this initial rice farming dispersal of Austronesians from Taiwan with rice impressions dating to the Neolithic (1900–1350 cal. BC), though there is no evidence to confirm this as domesticated rice. The rest of the rice evidence from the Philippines dates to the late prehistoric–early historic period (AD 1000–1500) showing a major gap. This perhaps suggests a lack of dispersal southwards, at least for this cereal but archaeobotanical sampling has also been limited. The rest of the rice evidence from island Southeast Asia is problematic. Both Gorman (1977) and Bellwood (2007) believe that rice was dropped from the original agricultural package leading to a reliance on other crops such as taro, bananas and sago, for which there is a small body of recent evidence (Barton and Paz, 2007; Paz, 2002). The few early reports (e.g. Gua Sireh and Niah Cave in Borneo) are husk impressions in pottery, and dating is poorly resolved but still probably *c*. 2000 BC at the latest. It is possible that rice spread to some islands, such as Borneo, from the mainland rather than via the Philippines. It should be noted that taro (*Colocasia esculenta*) is also often cultivated in wet-field systems (with probable methane output), and that these had evolved in the New Guinea highlands certainly before 3000 BC (Denham, 2009; Denham et al., 2003).

Systematically collected archaeobotanical evidence is very limited in Southeast Asia, which means that hard evidence for the nature of early cultivation systems is mostly lacking (Castillo and Fuller, 2010). The evidence is primarily derived from pottery with rice grain and chaff inclusions or impressions. In many instances, the occurrence of rice has been presumed to be a clear sign of cultivation with no definitive criteria used to establish the domestication status of rice, a topic normally dealt with in archaeobotany. Archaeological work so far conducted in the entire region shows fewer than 50 sites in Southeast Asia employed flotation and fewer than 30 sampled for phytoliths (Castillo and Fuller, 2010).

In mainland Southeast Asia, the record of rice is biased towards Thailand, but only two sites with confirmed domesticated rice based on the presence of spikelet bases occur there. Early domesticated rice evidence dates from about 2000 BC at Khok Phanom Di (Thompson, 1996). Earlier rice remains include grains from Ban Chiang in northeast Thailand (Bellwood, 2005) and phytoliths from sediment cores in the vicinity of Khok Phanom Di that indicate *Oryza* as early as 6000–5000 BC (Kealhofer and Piperno, 1996), but these are all plausibly wild types. From the Bronze Age at Ban Chiang (after 2000–1600 BC), rice is presumed to be domesticated and grown under naturally inundated, flood-plain conditions (White, 1995). The majority of Neolithic rice finds on the mainland are situated in low-lying coastal areas, interior river valleys and floodplains possibly indicating rainfed, lowland cultivation systems, including flood-prone areas. In a few well-sampled sites in central Thailand, rice appears quite late in the Metal Age (*c*. 800 BC), e.g. at Nil Kham Haeng (Weber et al., 2010). This can be contrasted with evidence for the presence of dry-cropped, introduced millet (*Setaria italica*) in the earlier levels at Nil Kham Haeng and at nearby Non Pa Wai from as early as *c*. 2300 BC (Weber et al., 2010). This indicates that in Thailand rice may have been initially adopted into dry-cropping agriculture and that wet-rice cultivation was a later development.

In the rest of Southeast Asia, we have rice impressions on pottery occurring mainly in the pre-Bronze Age (2200–1800 BC) in Cambodia but again with no real evidence for domestication. In Vietnam, Bellwood (2005) believes there is good evidence for rice cultivation from about 2000 BC onwards and the site of Dong Dau dating from the Neolithic to the Bronze Age has yielded domesticated rice grains (Glover, 1979). Throughout Southeast Asia there is little firm evidence on cultivation systems (Castillo and Fuller, 2010), although labour-intensive artificial paddy-field systems are likely to be rather later, and perhaps associated with the emergence of cities and states in the early centuries AD (e.g. Mudar, 1999).

A long history of use and late domestication: Rice in South Asia

The spread of rice agriculture in India can now be understood on broad geographical and chronological bases. Two plausible areas of initial rice domestication have been identified: the Gangetic basin, with a longer archaeobotanical record, and poorly studied Orissa (Fuller, 2006). Both areas show evidence for stands of native annual wild rice (*Oryza nivara*). In the Ganges region proxy indicators suggest environmental manipulation through vegetation burning from as early as the twelfth millennium BC, while associated rice phytoliths raise the possibility of rice use by the early Holocene (Singh, 2005). Archaeobotanical evidence from Lahuradewa dates early rice use, to at least *c*. 7000 BC if not earlier (Tewari et al., 2008), although this is plausibly the collection of wild rice or a form of management that did not result in the evolution of domestication traits (Fuller and Qin, 2009; Fuller et al., 2010). Clear evidence for cultivation starts from *c*. 2500 BC (Saraswat, 2004), while finds of domestic rice associated with more sedentary village sites date from 2000 BC (Fuller, 2006; Harvey et al., 2005). By 2000–1700 BC rice cultivation was established across northern India, including the Indus valley region, Gujarat and Rajasthan, and Orissa in the East (Fuller, 2006; Fuller and Qin, 2009).

We therefore see a period of approximately 500 years in the third millennium BC in which the transition from using wild rice (perhaps as a major component of subsistence) to the use of rice as a primary cultivated crop occurred. It is this same period in which it is hypothesized that morphological traits of domestication, such as non-dehiscent spikelets, became established in Indian rice. Genetic evidence indicates that the universal non-shattering mutation *sh4* probably spread by hybridization (Sang and Ge, 2007), perhaps in a relatively short period of time (cf. Zhang et al., 2009). And this has been hypothesized to occur in Northwestern India or northern Pakistan, in the centuries after 2000 BC when there is extensive evidence for the diffusion of several crops and harvesting technology from northern China, presumably via Central Asia (Fuller and Qin, 2009; Fuller et al., 2010; see also, Meadow, 1996). This same period sees the entry of western domesticates, especially wheat, into China (Flad et al., 2010; Frachetti et al., 2010). Although there is some traditional rice cultivation in parts of Central Asia, its antiquity is poorly documented; phytolith evidence from Tuzusai in southern Kazakhstan suggests some cultivation of rice by *c*. 300 BC (Rosen, 2001). This diffusion of *japonica* rice from temperate China need not imply cultivation in central Asia, but the long-distance trade in grains; recent evidence for Chinese broomcorn millet in burials of pastoralist-forager settlement illustrates this sort of process for this period (Frachetti et al., 2010). It should also be noted that
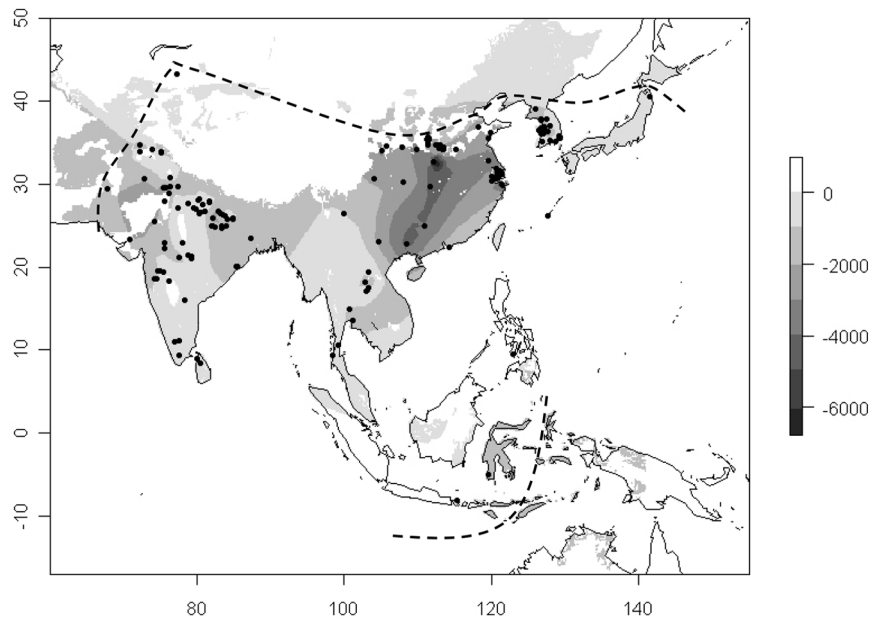
Figure 3. A map showing the reconstructed regional arrival time for rice in millennia BC, based on a preliminary GIS spatial model. This is based on an interpolation between archaeological evidence (black dots). Only areas where rice is cultivated at present are coloured. Details of method are described in the text. It should be noted that the arrival times are regional and smooth out much local variation. Also, note that rice arrival times for the areas that lack hard archaeological evidence (e.g. in Central Asia, Northeast China, Northeast India, Indonesia) are based on the nearest point with evidence. However, these areas (with the main exception being Indonesia), contribute relatively little to methane emissions. The dashed lines indicate the geographical limits of prehistoric evidence for rice

there is no evidence for an earlier diffusion of rice from Southwest China to northeast India: although hard archaeobotanical evidence is lacking through this region, the admittedly ambiguous historical linguistic evidence is congruent with the entry of Austroasiatic (Munda) speakers only after the establishment of indigenous millet-pulse farmers and spread of livestock i.e. *c.* 2000 BC (Fuller, 2003).

There is a hiatus, however, before rice cultivation is taken up in the Deccan, South India and Sri Lanka. It is not until the second half of the first millennium BC that we see archaeobotanical evidence and rice tempered pottery suggesting the use of rice as a main crop (Fuller, 2006; Fuller et al., 2010). It is possible, but still unsubstantiated, that the earliest rice in Sri Lanka should be associated with the earliest occupation at urban sites such as Anuradhapura at *c.* 900 BC, although recovered and directly dated rice finds are later (Deriyanagala, 1992; Young and Coningham, 2006). This final dispersal of *Oryza* in South Asia has been attributed in part to the spread of Buddhism, urbanism and irrigation technology into drier regions during the first millennium BC (Shaw and Sutcliffe, 2003; Shaw et al., 2007), and analyses of weed assemblages show a clear increase in wetland flora associated with rice during the Iron Age in northern and eastern India, suggesting that the development of wet-field cultivation was a major factor in the southward dispersal of rice (Fuller and Qin, 2009).

A simple geospatial model of the spread of wet-rice cultivation and methane emissions

The archaeological record of rice, summarized above, provides both chronological and geographical data on the spread of rice and wet-rice agriculture. From these data, we determined the earliest date of wet-rice cultivation in each area and the increase in the harvested area of rice for different assumptions about local areal expansion of wet-rice cultivation. From these results, we then provide an estimate of the extent of methane production from Asian rice in prehistory, which should be more accurate that previous attempts. Ruddiman and Thomson (2001) relate possible methane emissions from rice in Asia to population growth at a quasi-global level. However, working from population estimates towards methane emissions adds much uncertainty. Regional prehistoric population numbers have large uncertainties, while contemporary analyses show great variation in rice productivity between areas, which is not only a function of technological mastery but also of labour availability (Bray, 1986). In other words, agricultural land area and population density are not linked in a simple linear fashion (also, Ruddiman and Ellis, 2009). Our approach has been to spatially and chronologically bracket wet-rice land area estimates by modelling the start of rice cultivation, the start of wet-rice cultivation, and the areal expansion of this cultivation.

The first archaeological evidence for rice cultivation for each site was interpolated to create surfaces of the *regional arrival time* of rice (Figure 3). Regional arrival times do not correspond directly to the *local* start of rice cultivation at each location, but provide an age limit to rice cultivation between the archaeological sites. Thus, for example for northern India the regional arrival time falls between 3000 and 2000 BC, whereas around two foci in southern China it falls between 5000 and 4000 BC. These dates provide a lower time limit for the process in which rice cultivation expanded from certain regional foci toward surrounding local areas. To determine these lower time limits, the earliest sites in each area are more important than later sites, which only provide evidence for the subsequent expansion and continued cultivation of rice. Our interpolation method therefore gives greater weight to
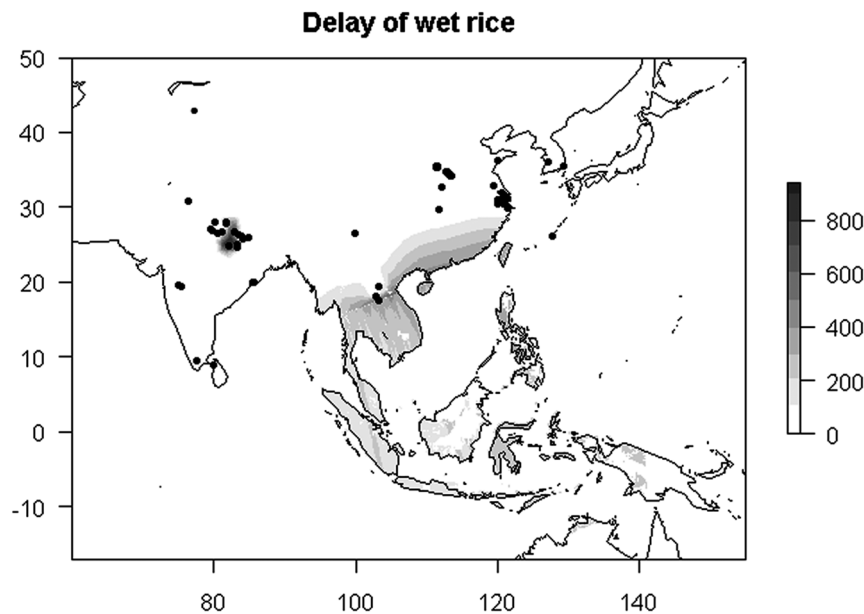
Figure 4. Interpolated surface of the 'delay' in the introduction of wet cultivation techniques subsequent to the first regional arrival of cultivated rice. The dots indicate the sites for which wet-rice cultivation was inferred from archaeobotanical evidence

the earlier sites. Details of the interpolation method are presented in the Appendix (available online). To achieve this, we used penalized triograms in combination with quantile regression (Koenker and Mizera, 1994), using R (R Development Core Team, Koenker, 2009). We visually determined the value of the smoothing parameter (lambda), taking into account the density of measurements. We set the quantile regression parameter (tau) to 0.1, giving greatest weight to the earliest 10% of the sites. We extrapolated the surface a short distance beyond the convex hull enclosing the observed locations, using ordinary kriging. The surface we obtained represents the arrival of rice, both irrigated and non-irrigated.

We have also taken into account the possibility that in certain areas the earliest recorded rice was not cultivated under wet conditions and hence did not contribute to methane emissions. In some areas there is evidence that wet cultivation techniques (bunding, irrigation) were introduced long after the introduction of cultivated rice. Figure 4 shows the inferred delay in the arrival of wet cultivation techniques subsequent to the arrival of cultivated rice (see the Appendix, available online, for methodological details). In parts of northern India, the arrival of irrigation seems to have taken at least 500 to 1000 years more than the introduction of domesticated rice. Indeed, most early rice is thought to be dry, supporting the idea that the introduction of irrigation was late in this area (after *c*. 1500 BC). Now this region is very prominent in the production of wet rice and methane (Xiong et al., 2009). In Indonesia, there is an absence for evidence either confirming or denying early irrigation; early rice was perhaps most likely rainfed, upland and largely a non-contributor to methane.

To model the areal expansion of paddy rice by, assuming a steady decrease in per capita land use for rice cultivation across the whole study area, as Ruddiman and Ellis (2009) do on a global scale, would fail to reflect spatial variation. Contemporary analyses show great variation in rice productivity between areas, which is not so much a product of technological mastery as of population pressure and labour availability (Bray, 1986; Hanks, 1972; cf. Boserup, 1965). Bray (1986) notes that migrants who occupied new regions dis-adopted the labour-intensive technologies they used in the places from which they originated, as land was more abundant around the new settlements. In medieval Europe technological innovation in cereal agriculture came to a stop after the population decrease of the fourteenth century (Slicher van Bath, 1966). Hence, land use efficiency did not steadily increase over time as a function of technological progress, but was mainly an effect of population density. Land use efficiency can therefore be fairly low even late in history in areas where population densities are relatively low. Additional evidence for a non-linear relationship between population density and land under rice comes from a spatial comparison. Currently, in Asia cultivated land (all crops) correlates spatially well with the *logarithm* of local population density ($r = 0.75$), while a linear correlation is far weaker ($r = 0.24$). (Determined with data from the HYDE 3.1 data base at a 5 min resolution (Klein Goldewijk et al., 2010, 2011).

From this we conclude that it is not unreasonable, in the context of this exploratory study, to couple land use directly to the logarithm population density (for which data are less uncertain than for cultivated land) and not assume a certain farming efficiency for different areas or periods. We conclude from this that while population increase approximates an exponential growth model, linear growth is a more reasonable model for cultivated land. It should be observed that the assumption of a linear decrease in land use per capita in Ruddiman and Ellis (2009) results in a roughly linear increase of total crop land over the last 12 000 years. For the period before AD 1000 we represent the early expansion of the area planted with rice by a linear growth model. We used a longitude-latitude grid with a resolution of 30 min. To model rice expansion within each grid cell, we linearly interpolated between the year rice cultivation and methane emissions started (zero) and the value attained by AD 1000.

To determine (1) the values of land under rice and (2) methane emissions in AD 1000, we scaled back the current values by multiplying with a factor representing population density (PD) increase in the period from AD 1000. This scaling factor was calculated for each grid cell with the following formula:

$$\text{Scaling factor} = \ln[(PD_{1000AD}/715) + 1] \,/\, \ln[(PD_{present}/715) + 1] \quad (1)$$

The value of 715 was determined by maximizing the linear correlation (r) between current population density and current crop surface. For these calculations, we used the rural population density and crop surface data from the HYDE 3.1 data base (Klein Goldewijk et al., 2010).

Our data for current land under rice are a compilation of subnational rice distribution data, for three different categories: upland rice, lowland rainfed rice and lowland irrigated rice. Many countries do not report the different types of rice cultivation in their rice distribution data. For those countries, this was estimated from other sources such as Huke and Huke (1997) for Asian countries. We used the latest data available and adjusted total area per country to that reported by the FAO for 2005–2007. For methane emissions, modern estimates have varied widely from the low 25.6 ×10^9 kg (= 25.6 Tg) of Yan et al. (2009) up to as much as 120· × 10^9 kg. The review by Ruddiman (2007) suggests a middle figure of 60 × 10^9 kg is to be preferred (after Reeburgh, 2003). We have provided estimates based on both the figure of Yan et al. (2009) and the higher figure of Reeburgh (2003) and Ruddiman (2007).

We choose AD 1000 as our reference year, as a new phase of large-scale land reclamation and infrastructure development started in the eleventh century in the Lower Yangtze, during the Song state (Bray, 1986). The Mekong, Irrawaddy and Chao Phraya deltas were only prepared for rice cultivation starting in the nineteenth century and similarly required large-scale engineering and organization. These environments were not available or had limited importance to prehistoric rice cultivators. Also, for the last 1000 years, population estimates incorporate historical information, while for earlier periods uncertainties increase (Klein Goldewijk et al., 2010). Hence, we think that our approach takes advantage of the information that is available, while using a straightforward approach for data-sparse periods, facilitating interpretation.

Using the methods outlined above, we generated 1000 year time-step maps of methane production from the rice cultivation areas of Asia (Figure 5). Although wet-rice cultivation started before 4000 BC and perhaps from 6000 BC, up to 3000 BC anthropogenic emissions of methane remained virtually undetectable according to our results, and only around 2000 BC they reached about 5% of the current values. Between 2000 and 1000 BC, increases in rice surface become linear in our model, as in this period paddy rice cultivation reached most regions in which paddy rice was important in later periods, including northern India. In AD 1000, rice methane emissions reached 37.5% of the current value i.e. at least 8.7· × 10^9 kg (based on the lower Yan estimate) or plausibly 22.5 × 10^9 kg (following the Ruddiman estimate). Based on a conversion of ~3.2 ppb methane in the atmosphere for 1· × 10^9 kg release (Ruddiman, 2007) we can bracket the atmospheric methane produced by rice at AD 1000 between a minimal 31 ppb and 72 ppb.

A methane contribution from Old World ruminant pastoralism: African and Asian expansions of the mid to late Holocene

Rice cultivation is not the only source of methane from traditional agricultural practices: methane is a natural product of the ruminant digestive system and should be produced in varying quantities by all the herded ungulates, including cattle, water buffalo, sheep and goat. Despite the lower output of stock-keeping per unit of land, livestock is less geographically limited. Methane-emitting rice is restricted geographically to regions of high rainfall and higher water-tables. This is in contrast to livestock herding, which has spread over the course of prehistory throughout drier and more agriculturally marginal environments. While a thorough, quantitative synthesis on the archaeology of ruminant pastoralism, through Eurasia and Africa, is beyond the scope of the present paper, we provide a preliminary consideration of this input, and some first maps that highlight the potential importance of the dispersal of livestock between 5000 and 3000 years ago throughout Africa and Asia.

The earliest domesticated caprines (sheep and goat) first appear in the Zagros regions of Iran and Iraq around 10 000 years ago. Following this a broader suite of Neolithic domesticates, including sheep, goat, cattle and pigs, spread throughout the Near East into the eastern Mediterranean (Zeder, 2005, 2008), eventually reaching central Europe and mainland Britain by the mid-fourth millennium BC (Rowley-Conwy, 2004). The initial spread of livestock from the Near East into Europe therefore pre-dates the earliest rise in Holocene methane levels. Instead, we need to look into subsequent pastoral intensification, beyond the traditional focus of livestock origins, and consider the dispersal of domestic ruminants through other regions.

African herd dispersal (Figure 6)

Domestic cattle are present in North Africa by at least the mid-sixth millennium BC, although claims have been made for their presence as early as the mid-eighth millennium BC (Close and Wendorf, 1992; Gautier, 1984). From here, domestication appears to have spread westwards across the Sahara and southwards along the Nile Valley. Cattle are present at Gabrong and Baradigiué in the Tibesti in the mid fifth millennium BC (Barich, 1987; Gautier, 1984), and at Adrar Bous in the Ténére desert of Niger by 4000 BC (Clark et al., 2008). After 2500 BC the deterioration of conditions in the Sahara and southward shift in the position of the Inter Tropical Convergence Zone prompted the movement of cattle into Sub-Saharan West Africa (Casey, 1998; Clark, 1976; Munson, 1980). Recent excavations in the Lower Tilemsi Valley in northeastern Mali have revealed intensive herding activities, inclusive of both cattle and ovicaprines by the mid-third millennium BC (Manning, 2008a, b). Shaw (1977) notes that any movement of pastoral populations prior to this time would have been restricted by the disease vectors common to Sahelian West Africa, notably malaria and trypanosomiasis, which were only alleviated by a southward displacement of the tsetse barrier *c*. 1700 BC. From this point onwards, pastoralists moved rapidly into Sub-Saharan Africa, reaching the forested zones of central Ghana by the early second millennium BC.
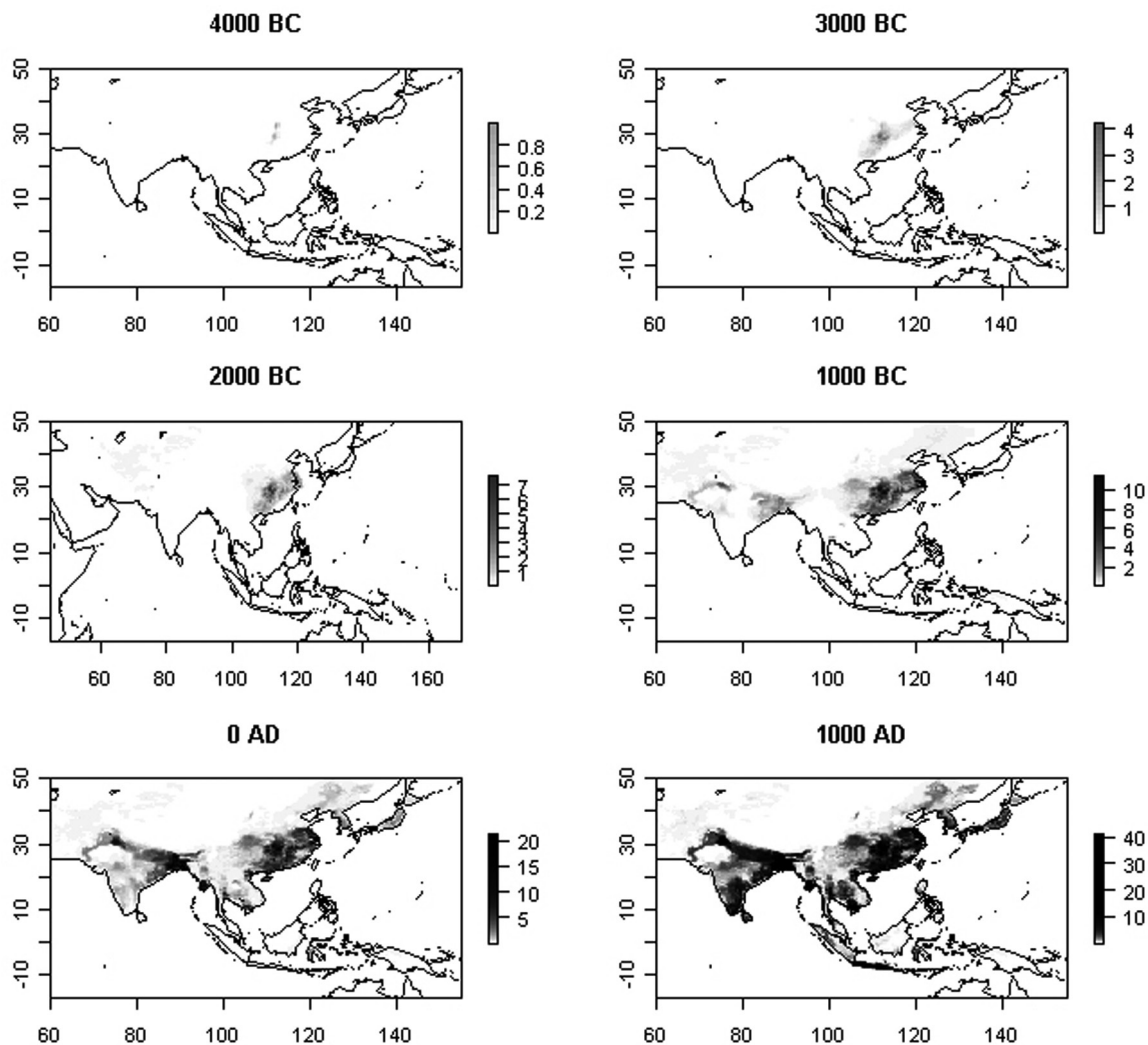
Figure 5. A model of methane emissions from irrigated or lowland rainfed rice in 1000 year time slices. Numerical scale indicated by shading represents emissions of each pixel in 10^6 kg CH$_4$/yr. Each pixel measures 0.5° × 0.5°. The model assumes linear growth of methane emissions from the moment of the first arrival of wet-rice cultivation (methane emission = 0) to AD 1000. The AD 1000 methane emission values were obtained by scaling back the current values of methane emission, in logarithmic proportion to rural population growth in the period AD 1000–2000 (see main text)

On the eastern side of the continent, a similar southward shift in pastoral populations was taking place. Domestic cattle and caprines appear around Lake Turkana in northern Kenya by 4000–3000 BC, making their way into southern Africa by around 2000 years ago. The widespread distribution and intensification of herding activities in Sub-Saharan Africa took place in a relatively short period of time between *c.* 3500 and 1000 BC. This was also a time of high-level diversification in livestock morphology, with dwarfism occurring as early as the first millennium BC (MacDonald and MacDonald, 2000), indicating rapid migration and adaptation to newly opened ecological zones.

South and East Asian herd dispersal (Figures 7, 8)

Of great significance is that the spread of domesticated ruminants into the regions of Asia which can support the highest population numbers, was delayed until after 3000 BC. Sheep and goat, and perhaps some taurine cattle, spread eastwards with the initial Neolithic dispersal from the Near East, reaching parts of central Asia and across the Iranian plateau to Baluchistan and the western margin of the Indus valley (Fuller, 2006; Meadow,

1996). Along this eastern frontier of expanding agropastoralism, there is growing evidence for additional domestication events, including zebu cattle in Pakistan (Chen et al., 2010; Meadow, 1996), and additional domesticated lineages of goats and sheep (Naderi et al., 2008; Pedrosa et al., 2005). The lower Indus valley region was also a likely centre for another bovine domestication of water buffalo (Meadow and Patel, 2003; Patel and Meadow, 1998). Nevertheless, east of the Indus region, into monsoonal India the first signs of any pastoralism date from *c.* 3500 BC (Patel, 2009), and livestock only become widespread closer to 2000 BC (Figure 7). What is striking, however, is how rapidly domestic fauna spread during this period, reaching the southern states of Karnataka and Andhra Pradesh by at least 2500 BC, and the middle Ganges by 2000 BC. By 1000 BC or shortly thereafter pastoralism was established as part of the Megalithic Iron Age cultural complex through most of the far south, including Tamil Nadu and parts of Sri Lanka.

In China, although there was a long tradition of indigenous domesticated animals, especially dog and pig (Larson et al., 2010; Yuan, 2010; Yuan and Flad, 2002), domesticated ungulates appear to be largely introduced within the past 5000 years
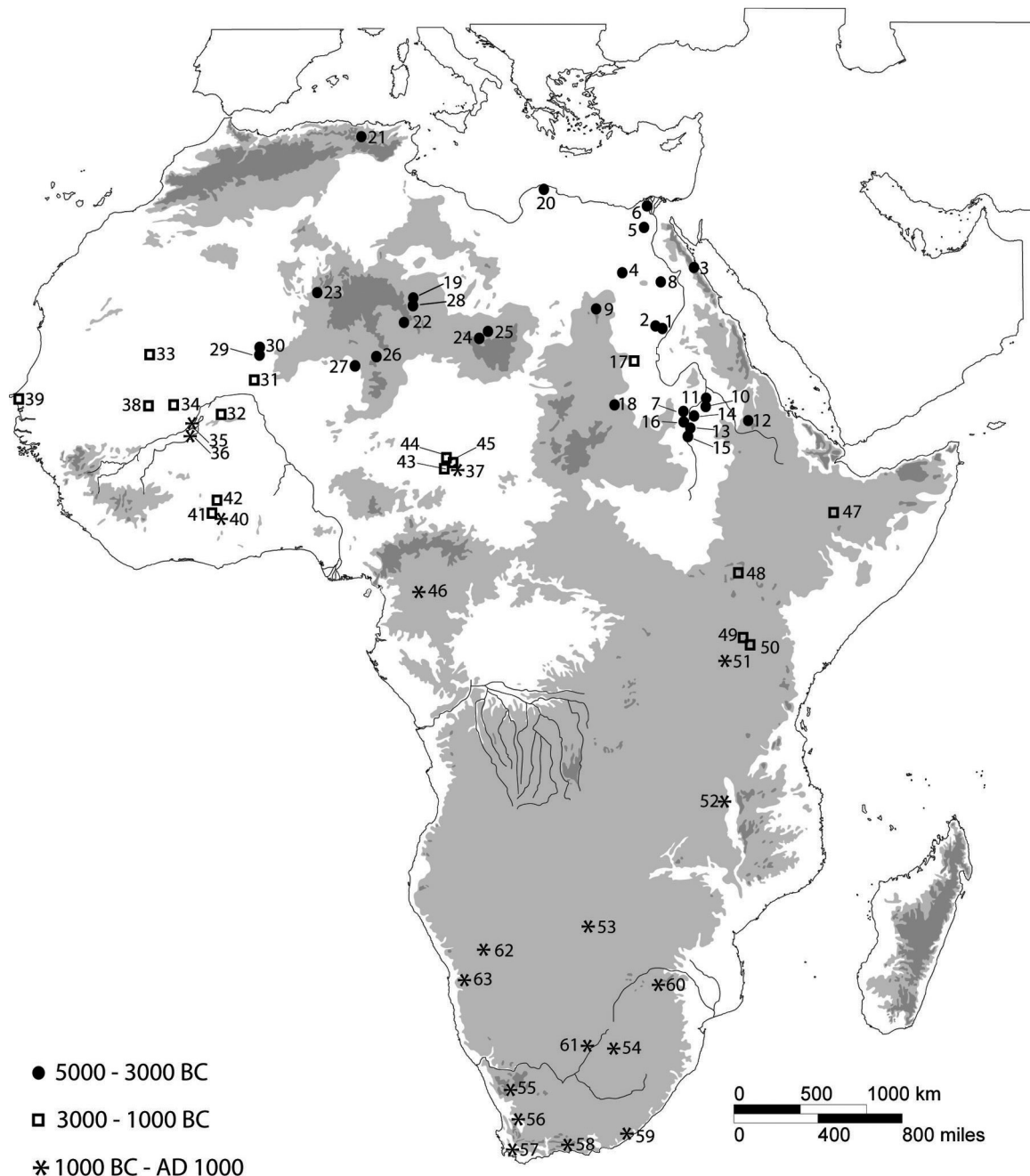
Figure 6. The spread of livestock in Africa (cattle, sheep/goat), in broad time slices, based on representative archaeozoological data sets (Table S2, available online). Sites numbered: 1, Bir Kiseiba; 2, Nabta Playa; 3, Red Sea Hills; 4, Dakleh Oasis; 5, Fayum A sites; 6, Merimda–Benisalama; 7, Esh Shaheinab; 8, Kharga/E-76-7, E-76-8; 9, Gilf el Kebir; 10, Shaqadud; 11, El Kadada; 12, Kashm el Girba; 13, Kadero; 14, El Zakiab; 15, Um Direiwa; 16, El Nofalab; 17, Laqiya; 18, Wadi Howar; 19, Ti-n-Torah; 28, Uan Muhuggiag; 20, Haua Fteah; 21, Grotte Capeletti; 22, Ti-n-Hanakaten; 23, Meneit; 24, Gabrong; 25, Baradigiué; 26, Adrar Bous; 27, Arlit; 29, Asselar; 30, Tessalit; 31, Lower Tilemsi Valley; 32, Windé Koroji; 33, Dhar Tichitt; 34, Kolima Sud; 35, Dia Shoma; 36, Jenne Jeno; 37, Daima; 38, Kobadi; 39, Chami; 40, Boase 6; 41, K6; 42, Ntereso; 43, Gajiganna; 44, Kursakata; 45, Mege; 46, Gaji2, Koobi Fora ridge; 47, Gaji4, Dongodien; 48, Gtji12, Enkapune ya Muto; 49, Guji13, Salasun; 50, Toteng; 51, Wonderwerk; 52, Spoegrivier; 53, Kasteelberg A; 54, Die Kelders; 54, Byneskranskop; 55, Blombos cave; 56, Nelson Bay cave. Compiled from various sources; for references see text

(Figure 8). Sheep, which have their origins in Southwest Asia appear in central China, the Yellow River basin between 3000 and 2500 BC. By 2500 BC the first evidence for western crops also occurs on the northwest margins of central China (Li et al., 2007). However, these crops did not take hold quickly, with only wheat becoming rather more widespread in China closer to 2000 BC (Flad et al., 2010; Fuller and Zhang, 2007; Lee et al., 2007) Yet another introduction from the west was cattle (*Bos taurus*), which are confirmed from Shantaisi and Peiliangtai at *c.* 2000 BC (Huang, 2010; Yuan, 2010). The earliest confirmed goats are

found in late Neolithic contexts at Xinzhai, *c.* 2000 BC (Huang, 2010) and Bronze Age Erlitou, at *c.* 1800 BC (Yuan, 2010; Yuan and Campbell, 2009), although one might expect a small number to have accompanied early sheep. Thereafter during the course of the Bronze Age, cattle and sheep become prominent parts of pastoralism, diet and sacrifice in north/central China (Chang, 1980; Yuan, 2010).

In southern China, data are fewer and issues are more complex. South of the Yangtze today, cattle gene pools include substantial genetic elements from Indian zebu cattle (*Bos indicus*)
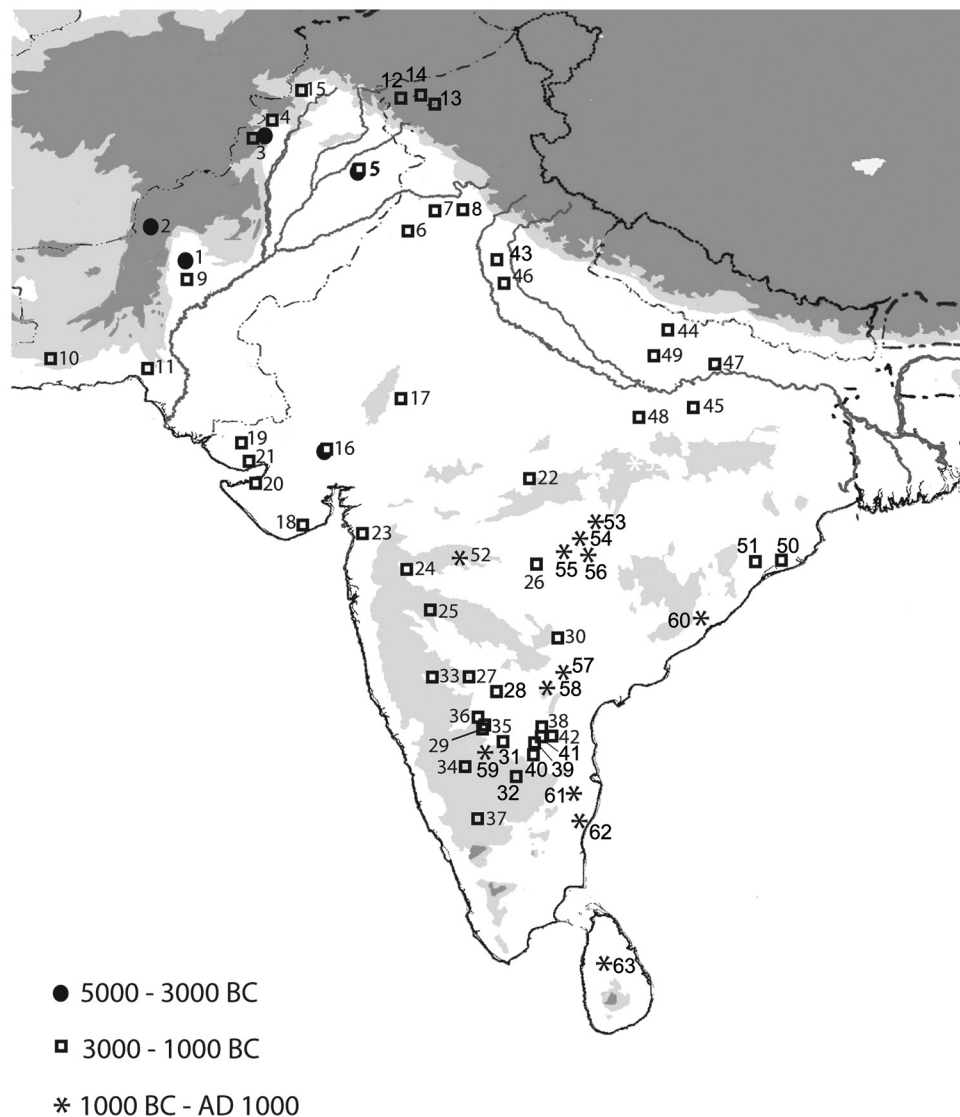
Figure 7. The spread of livestock in South Asia (cattle, water buffalo and/or sheep/goat), in broad time slices, based on representative archaeozoological datasets (Table S3, available online). Sites numbered: 1, Mehrgarh; 2, Kili Ghul Mohammad; 3, Sheri Khan Terakai, Lak Largai & Lewan; 4, Tarakai Qila; 5, Harappa; 6, Kalibangan; 7, Rupar; 8, Bara; 9, Nausharo; 10, Miri Qalat; 11, Balakot; 12, Kanishpur; 13, Gufkral; 14, Burzahom; 15, Loebanhr; 16, Loteshwar; 17, Balathal; 18, Padri; 19, Dholavira; 20, Kuntasi; 21, Shikarpur; 22, Kayatha; 23, Kaothe; 24, Daimabad; 25, Inamgaon; 26, Tuljapur Garhi; 27, Kodekal; 28, Utnur; 29, Kudatini; 30, Budihal' 31, Banahalli; 32, Palavoy; 33, Terdal; 34, Hallur; 35, Sanganakallu; 36, Tekkalakota; 37, T. Narsipur; 38, Rupanagudi; 39, Hanumantaraopeta; 40, Biljapalle; 41, Nagarajapalle; 42, Peddamudiyam; 43, Alamgirpur; 44, Lahuradewa; 45, Senuwar; 46, Lal Qila; 47, Chirand; 48, Mahagara/ Koldihwa; 49, Khairadih; 50, Golbai Sassan; 52, Gopalpur; 52, Bhokardan; 53, Bhagimohari; 54, Veerapuram; 55, Brahmagiri; 56, Nagarjunakonda; 57, Nagarjunakonda; 58, Veerapuram; 59, Brahmagiri; 60, Jami; 61, Sanur; 62, Arikamedu; 63, Anuradhapura. Compiled from various sources, including Moorti (1994); Chattopadyaya (2002); Meadow and Patel (2003); Fuller (2006)

(Chen et al., 2010), which had spread eastwards out of India in later prehistory. In addition water buffalo populations today seem to be related to the remnant wild populations of South Asia (*Bubalus bubalis*), which must have replaced an earlier indigenous wild buffalo type (*Bubalus mephistopheles*). Current data suggest that South Asian domesticated buffalo were introduced not earlier then *c.* 1000 BC (Yang et al., 2008; Yuan, 2010). Nevertheless what constitutes the original wild range of 'South Asian' buffalo is unclear, as populations could have been extirpated from the upper Yangtze regions such as Yunnan and Sichuan. In Central and Eastern China early finds of *B. mephistopheles* are widespread, and recent data from ancient DNA in central China (Yang et al., 2008) and kill-off patterns from the Lower Yangtze suggest these were wild (Liu et al., 2004). It remains possible that these were separately domesticated and later replaced by introduced

breeds from South Asia. If this was the case it is likely to have only been in small numbers, which might be supported by evidence for stone tipped ploughs by 3000 BC in the Lower Yangtze (Fuller et al., 2008). Nevertheless, this would have been in very small numbers only and has not been considered in our map of early pastoralism. The Lower Yangtze evidence in general points to wild hunting, heavy fishing, and only fairly limited pig keeping throughout the Neolithic up to at least 2000 BC (see Yuan et al., 2008).

Data tracking the spread of livestock in Southeast Asia remains even more problematic (Figure 8). The Neolithic in Southeast Asia is characterized by the presence of domestic pigs and dogs (Higham, 2002a, b), alongside rice cultivation – as well as millet in some areas (Weber et al., 2010). Although 'cattle' (Bos/bovine) bones are reported from many sites, their status as domesticated
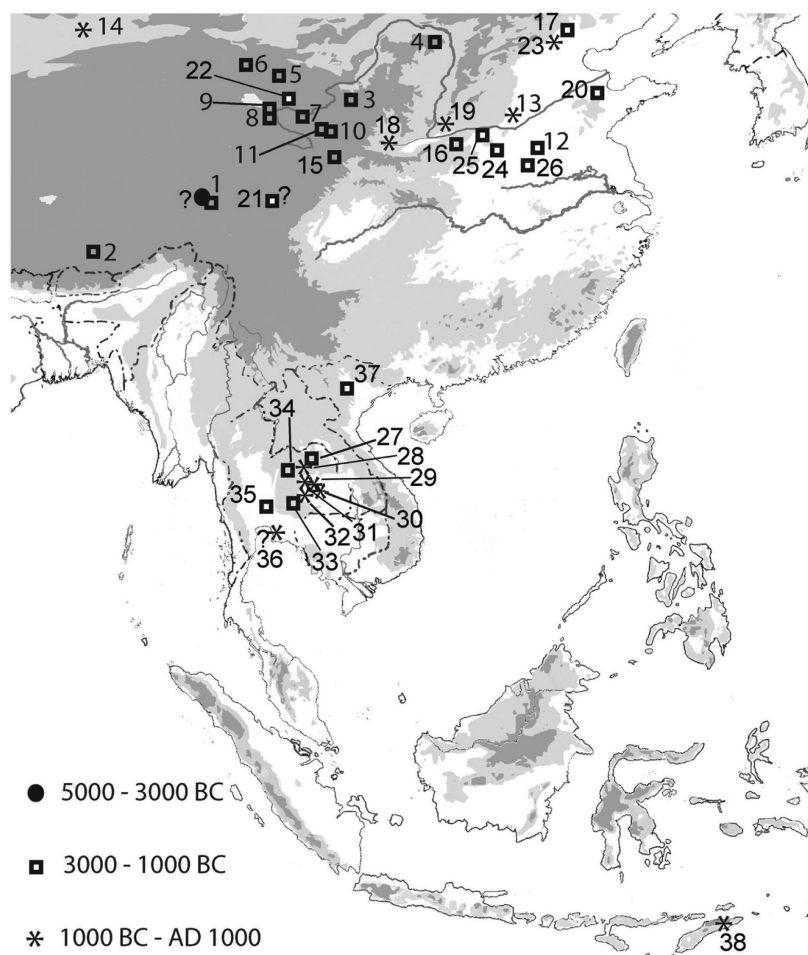
Figure 8. The spread of livestock (cattle, water buffalo and/or sheep/goat) in East and Southeast Asia, in broad time slices, based on representative archaezoological data sets (Table S4, available online). A few problematic identifications are included, indicated by: ?. Sites numbered: 1, Karuo; 2, Qugong; 3, Linziliang; 4, Zhukaigou; 5, Donghuishan; 6, Huoshaogou; 7, Dahezuang and Qinwejia; 8, Zhongri; 9, Xiangangou; 10, Shizhaocun; 11, Xishanping; 12, Shantaisi; 13, Huayuangzhuang; 14, Chawuhugoukou; 15, Dalijiaping; 16, Xinzhai; 17, Zhangying; 18, Zhouyuan Zhuangli; 19, Qucun; 20, Tonglin; 21, Yingpanshan; 22, Hetaozhuang; 23, Zhenjiangying; 24, Wadian; 25, Erlitou; 26, Pingliangtai; 27, Ban Chiang; 28, Ban Na Di; 29, Ban Chiang Hian; 30, Ban Tha Nen; 31, Non Chai; 32, Noen U-Loke; 33, Ban Lum Khao; 34, Non Nok Tha; 35, Non Pa Wai; 36, Nong Nor; 37, Phung Nguyen; 38, Uai Bobo. Compiled from various sources, including, Glover (1986); Higham (2002); Flad et al. (2007); Huang (2010); Lu (2010); An and Chen (2010); Yuan (2010)

or local hunted animals remains a challenge. In Southeast Asia one must also contend with wild populations of *Bos javanicus*, *Bos suvali*, *B. gaurus*, and *Bubalus* (Grove, 1985). In addition, both *B. javanicus* and *B. gaurus* have been subjected to separate domestication processes, although these remain undocumented. In traditional Southeast Asia buffalo are especially important in the trampling and tillage of rice paddies, whereas *Bos indicus* is a widespread beef animal. Whether both these species spread from India, and when, is unknown. Genetic evidence for two gene pools in buffalo make a distinct Southeast Asian domestication possible (Kumar et al., 2007; Lau et al., 2002). Foot bone pathologies in buffalo bones from Ban Chiang have been taken to suggest tillage at that site, but whether this should be dated to the late Neolithic or late Metal Age remains unclear (Higham, 1975; Higham et al., 1981). In summary, Southeast Asian subsistence is only likely to have contributed to the growth of global cattle herd populations after 1000 BC, whereas the dispersal of livestock through India and China indicates major expansions of cattle between 3000 and 2000 BC.

Discussion

Trends in both wet-rice area and livestock spread mirror the later Holocene methane curve (Figure 9). Our data base for rice is currently sufficient to build general models of the areal extent and methane output of rice. Based on a fairly simple set of assumptions, we can see that the growth of wet-rice lands should produce a logarithmic growth in methane emissions significantly increasing from 2500 to 2000 BC, but especially after this date. This appears to be a reasonably good fit with the general trend in the observed methane data, although we would question whether the wet-rice methane output was sufficient between 3000 and 2000 BC to account for the full divergence of atmospheric methane from the expected trend. In addition, large geographical gaps in the data mean that some of the interpolated rice area may be an overestimate. In addition the use of an AD 1000 data set for setting the limits of potential rice lands, while preferable to a modern map, still exaggerates the likely prehistoric distribution. Both of these points suggest that our rice-derived methane output may
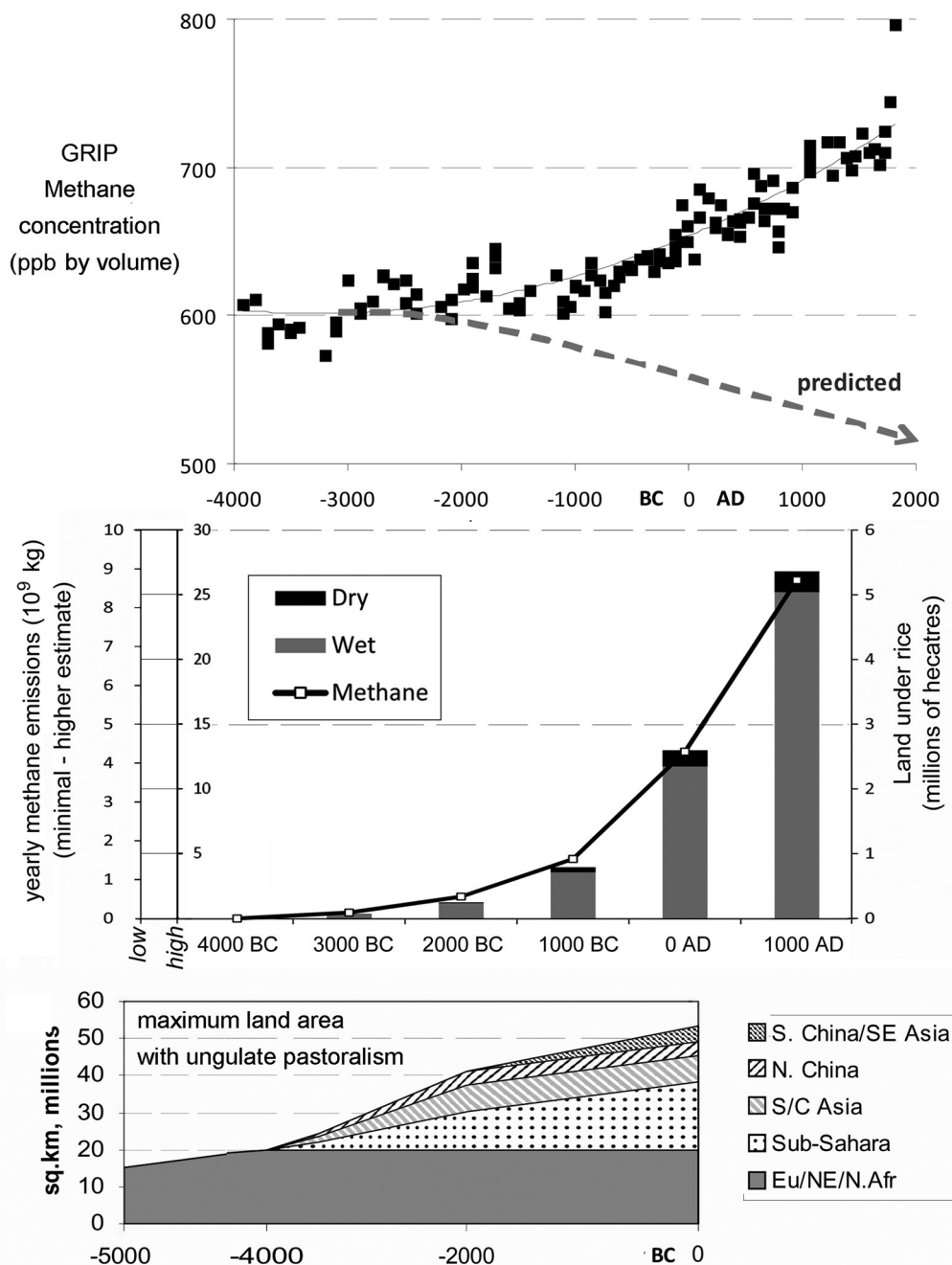
Figure 9. The correlation between measured atmospheric methane levels from the Greenland Ice Core (GRIP) data sets (top), with our estimates of land area and methane emissions from rice (middle), and our estimate of maximal land area over which ungulate pastoralism has spread (bottom). GRIP data show measured atmospheric methane and the predicted trend based on comparisons with previous interglacials (after Ruddiman and Thomson, 2001). For methods used to derive rice emissions see discussion in Section 'A simple geospatial model of the spread of wet-rice cultivation and methane emissions'. Maximal land area of pastoralism was estimated by hand-drawn polygons over land areas using an online area-calculator tool (http://www.freemaptools.com/area-calcukatorcalculator.htm)

be a slight overestimate. Based on the higher figure of modern methane output from rice ($60 \cdot \times 10^9$ kg, following the Ruddiman estimate). we can estimate this to account for 72 ppb of atmospheric methane. This would account for about 80% of the of apparent 90 ppb rise in anthropogenic methane by AD 1000 based on ice core data.

The dispersal of cattle, especially between 3000 and 1000 BC, provides a plausible source for additional anthropogenic methane. Our data base represents only a crude first attempt, and we are not yet able to attempt spatial modelling and quantification as we

have done with rice. As an initial attempt to give some semi-quantitative assessment, we have estimated the maximum land area over which pastoralism had spread in three broad periods. While the initial spread, between 8000 and 3000 BC covered the most ground, it also included large areas which have very low carrying capacities, such as the Sahara and Arabian deserts and the Iranian plateau. However a nearly equivalent land area saw the introduction of cattle herds between 3000 and 1000 BC, and much of this area was reached in the period of 3000–2000 BC. Significantly this included the savannah and savannah-woodland

zone south of the Sahara, monsoonal India, and the greater Yellow River basin of China. All of these zones are likely to have had dense human populations and substantial carrying capacities for cattle or ovicaprines. As such we suggest that during this period the methane from livestock may have been at least as important an anthropogenic methane source as rice. However, after 1000 BC the spread of livestock was much less significant, and it was by this time that we find substantial evidence for an increase in wet-rice land area and a steep, near-linear increase in methane production.

Our data and models, while they require further refinements, demonstrate the importance of accumulation, critical analysis and quantification of archaeological data, in assessing past human influences on atmospheric gases and global climate. While the anthropogenic nature of late-Holocene methane levels may be deduced by comparisons across interglacials, the archaeobotanical and archaeozoological data provide real proxy data for the human activities that would have contributed to methane output. Nevertheless, there is further work to do. There are obvious gaps in current evidence, both geographically and chronologically. Equally important is that data are collected, studied and quantified systematically and to high, current standards. Older data may tell us that rice was present, but not whether it was dry- and wet-cropped or its relative contribution to agriculture. Further research on refining the quantification and analysis of rice archaeobotanical assemblages is needed.

One weakness in our current model is that we have assumed that the proportion of rice versus other crops for any given region was comparable with contemporary proportions, but the dominance of rice was likely to be less in the past. Further modelling could take into account the proportions of rice versus other crops and foodstuffs at various sites and periods. For rice we need to refine the estimation of the quantitative relation between human population density and cultivated land that is specific to the rice in the regions of interest, which takes into account available technology and practices (for instance, the occurrence of tools in the archaeological record). In addition we should work to refine our AD 1000 baseline, and to improve our estimates of past population densities from archaeological settlement data.

In terms of zooarchaeological data, we need to follow a similar process for rice and develop some baseline data from which to interpolate potential herd density (carrying capacity) and to factor in the relationship between herd size and human population density. Just as there are non-linear shifts in the human–rice population equation resulting from intensification (Ruddiman and Ellis, 2009), so too shifts in animal exploitation strategy such as from primary products (meat) to secondary products (milk, wool, traction) will change the size of herds that people must maintain. Is there a step increase in herd size/density when pastoralists move towards using large herds as 'banks' of wealth rather than 'walking larders'; when does this occur in different regions? And at what stage in the history of stock-keeping did herders begin diversifying breeding stocks in order to exploit maximum land area. For animals we need to develop and refine such estimators. Ultimately we should aim for Boserupian land use sequences specific to rice-based economies, and to various herding systems.

Trends in cultural evolution have been non-linear, but they have involved recurrent dynamics. Archaeology provides access to comparative trajectories in regional histories of human energy extraction and environmental change. While archaeologists have long been interested in local impacts on the environment, and the

role of regional environmental changes on human social systems, we have aimed to show that archaeology can also contribute to a refined understanding of how the sum of local environmental impacts may also have global repercussions.

Acknowledgements

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