1. Introduction

Early agriculture has always been a pivotal point of discussion in archaeology, whether as Childe's (Childe, 1936) 'Neolithic Revolution' or, more recently, as a contender for the start of the Anthropocene (Ruddiman, 2003). Much of the focus, however, has been on 'origins' and on drawing out the paths along which farming spread from the supposedly few centres of domestication such as South-west Asia and East Asia (e.g., (Ammerman and Cavalli-Sforza, 1971; Renfrew, 1987, 2000; Bellwood and Renfrew, 2003; Bellwood, 2004; Fuller, 2003a, 2003b, 2003c; Fuller and Murphy, 2014; Kingwell-Banham et al., 2018, Kingwell-Banham et al., 2015). In pursuing agricultural origins, the focus has been on the 'when' and 'where' of early crop domestication. Much less is known about the 'how' of early farming: the strategies employed, the impact of environmental constraints, and the actual ecological 'niches' created by early farmers in different regions. Understanding the nature of early farming warrants an understanding of different aspects of agroecology such as manuring, tillage, water management, growing cycles and rotation regimes.

Particularly in South Asia, the local environmental context of agriculture, as well as the diversity of human strategies across this expansive landmass, remain to be thoroughly studied. Historically, the Indian subcontinent has long been on the sidelines of theory formulation, and its archaeology studied mostly in comparison to other parts of the world such as East Asia and South-west Asia. In terms of the emergence of agriculture, the region has been considered less as a site of change and innovation in and of itself, and more as a receptacle of domesticates, peoples, and ideas from other parts of the world (e.g., (Ammerman and Cavalli-Sforza, 1971; Renfrew, 1987; Bellwood and Renfrew, 2003; Bellwood, 2004), though recent work (e.g., (Kajale 1991; Misra 1999; Saraswat 2005; Fuller 2006a, 2006b; Fuller 2011; Fuller and Murphy 2014) has examined different regions of the Indian subcontinent as centres of early farming and possibly of domestication.

Recent work using weed ecology and crop stable isotope analysis in Europe and western Asia has built up a detailed understanding of the ecology of early farming regimes, their sustainability and social implications (Bogaard et al., 2016, Bogaard et al., 2013, Bogaard and Arbogast, 2016, Bogaard, 2015; Styring et al., 2016a, 2016b, 2017; Bogaard et al., 2016). Given the vast geographical and climatological diversity of India – ranging from extremely arid desert to flood-prone alluvial plains to mountains – there existed a myriad of traditional agricultural strategies until the Green Revolution in the latter half of the 20th century. While the introduction of new high yielding varieties of seeds, technological advancements, and extensive fertilisation and pest control measures in 1960s through the Green Revolution was a major force in achieving food security in India, this process led to the loss of distinct indigenous landraces of crops like rice, millets, and different pulses (Eliazer Nelson et al., 2019). An understanding of the long-term agricultural strategies in such an immensely diverse and populous region can serve to illuminate wider considerations of the impact of farming and the future of sustaining the world population. Therefore, the 'how', i.e. the nature of early agriculture, becomes crucial in studying the archaeology of the region.

This study is one of the first of its kind, utilising stable carbon and nitrogen isotope analysis of well-preserved botanical remains to understand aspects of early farming ecologies (i.e. crop growing conditions, farming strategies, and the impact of environmental constraints) in different parts of the Indian subcontinent over the long term. Remains from three Neolithic-Chalcolithic sites in East India (Harirajpur-Bang, Golbai-Sasan, and Gopalpur), and two Deccan sites – Sanganakallu-Kupgal, a Neolithic site, and Paithan, an Early Historic site (300 BCE to 550 CE) – were analysed to illuminate the variation in farming ecologies across time (from Neolithic to Early Historic) and across space (the 'wetter' Eastern Coastal Plains versus the semi-arid Deccan).

2. Background to the region

The diverse physical geography of India (Fig. 1) plays an important role in shaping rainfall (especially the movement of monsoon winds), soil type and human population density. Therefore, an attempt to understand past agricultural systems in this region must, necessarily, take account of these geographical differences. The eastern Indian sites of Harirajpur-Bang (Khurda district), Gopalpur (Nayagarh district), and Golbai Sasan (Khurda district) are located in the lowland coastal region of Odisha state. This region receives approximately 1500 mm of average rainfall annually, courtesy of the northeast monsoon and southwest monsoon rains, though the latter is the major contributor (India Meteorological Department, 2012; Guhathakurta et al., 2020a). A number of rivers such as Mahanadi, Brahmani, Baitarani, Rushikulya, and Subarnarekha flow through these coastal plains and their rich alluvial deposits provide a fertile environment for agriculture. In contrast, Paithan (Aurangabad district, Maharashtra) and Sanganakallu-Kupgal (Ballari district, Karnataka) are located on the northern and southern parts of the Deccan Plateau, respectively. This region does not benefit from the full effects of the monsoonal rains due to its location on the leeward side of the Western Ghats, which act as a physical barrier to the monsoon winds, as well as due its distance from the contributions of the northeast monsoon winds. The semi-arid region is drier than the eastern coast and receives a mean annual rainfall of approximately 500–700 mm, the majority of which occurs as a result of the southwest monsoon (India Department Rainfall Atlas of India, 2012; Guhathakurta et al., 2020b, Guhathakurta et al., 2020c).

The eastern Indian coastal state of Odisha demonstrates evidence of a distinct Neolithic tradition (Fuller and Murphy, 2014). While the archaeology of this part of the Indian subcontinent has not been subjected to extensive studies yet, two different kinds of sites have been discovered so far: mound settlements and shallow (in terms of the depth of archaeological material) upland sites. Neolithic-Chalcolithic mound sites like Harirajpur-Bang, Golbai Sasan, Gopalpur, Deltihuda, and Suabarei have provided an initial picture of early farming communities in the region. Beginning approximately in the middle of the 2nd millennium BC with the movement of agropastoral communities and/or specific crops to the region, the Neolithic in Odisha is characterised by a set of domesticated crops (like rice, horsegram, mung bean, millets, and pigeon pea), exploitation of fruit trees, settled villages, ceramic utensils and objects, herding of domesticated cattle, and occasional hunting of wild animals (Kar et al., 1998; Mohanty et al., 2012; Kingwell-Banham et al., 2018). While the region was initially considered a site of independent domestication of rice (e.g., Fuller 2006a, 2006b; Harvey et al., 2006), recent archaeobotanical research and targeted radiocarbon dating have shown that rice was likely introduced fully domesticated from the Middle Ganga region (Kingwell-Banham et al., 2018) alongside a package of other domesticated crops and animals. Preliminary data also suggests that the region saw the independent domestication of pigeon pea, and early arboriculture in the form of carbonised fruit peel and nut shell fragments (Kingwell-Banham et al., 2018).

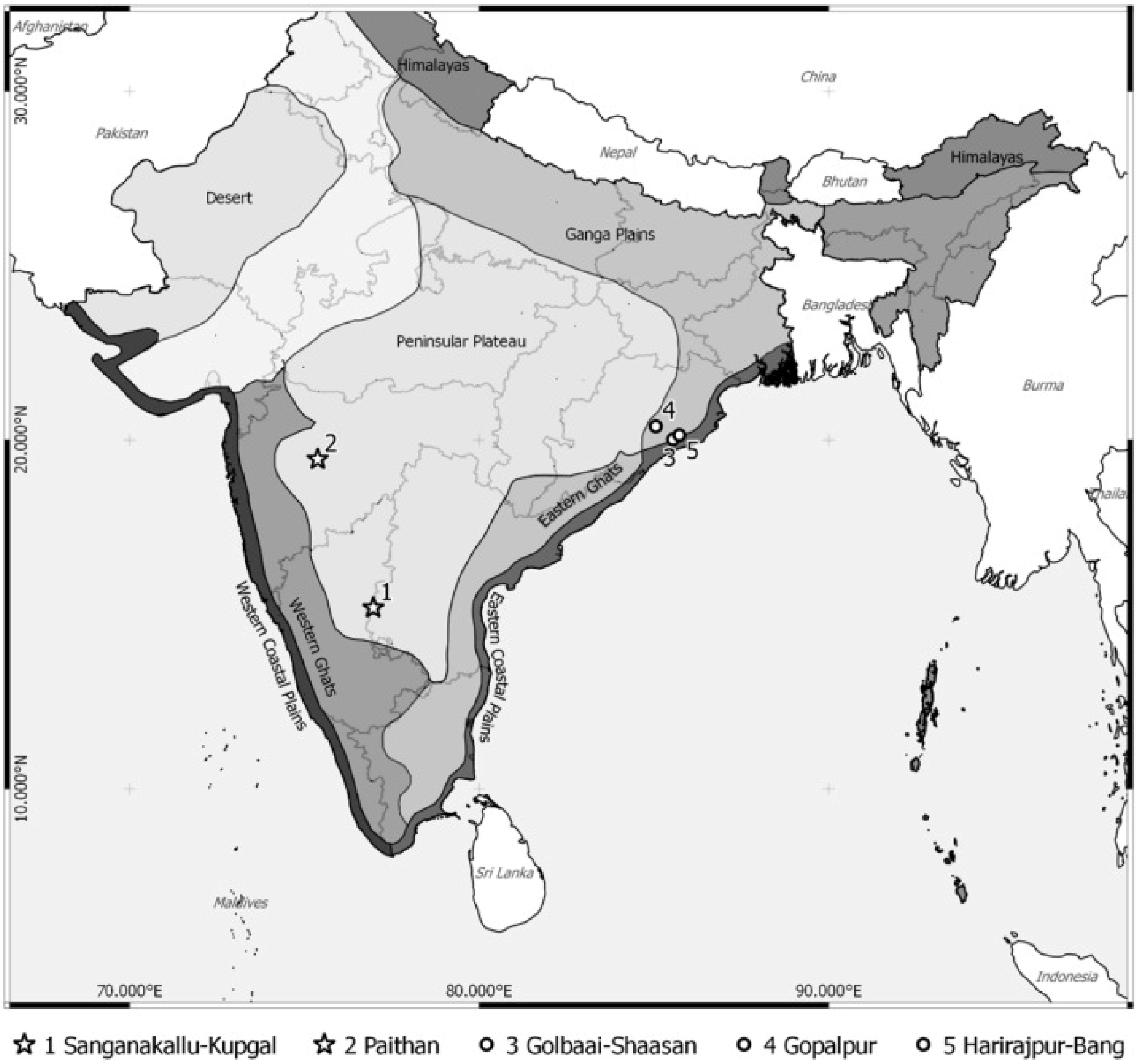

Fig. 1. Map of sites from the study shown in their geographical context. The Deccan sites are indicated with a star icon, and the East Indian sites are shown as circles on the map."

In contrast to East India, the Deccan Plateau, especially the southern part, has been very well studied and over two hundred Southern Neolithic sites have been systematically excavated to date (Kingwell-Banham et al., 2015). Roughly fifty per cent of the sites in the southern region are ashmounds (anthropogenic mounds made of burnt cattle dung and cultural material) (e.g., Allchin 1963; Allchin et al., 1982; Fuller 2006a, 2006b; Fuller et al., 2007; Boivin et al., 2018). The Southern Neolithic tradition starts in the 3rd millennium BC as small agropastoral communities likely with introduced domesticates from the North. By the middle of the 3rd millennium BC, the first ashmounds begin to appear in the archaeological record, but clear evidence for the Southern Neolithic crop package (including plants like wheat, barley, millets, and pulses which indicate year-round multi-season cultivation) is present only from c. 2000 BC (Fuller 2006a, 2006b; Boivin et al., 2018). Moreover, the southern part of the Deccan (southern Karnataka and south-west Andhra Pradesh) is believed to have been a site of independent agricultural origins, i.e. domestication of millets, Brachiaria ramosa and Setaria verticillata, and pulses, Macrotyloma uniflorum and Vigna radiata in the Neolithic (e.g., Korisettar et al., 2001a, 2001b; Fuller 2006a, 2006b; Fuller et al., 2007; Fuller 2011; Fuller and Murphy 2014; Kingwell-Banham et al., 2015; Murphy and Fuller 2017; Boivin et al., 2018). By c.

800 BC rice cultivation is adopted into this established multi-seasonal agricultural practice (Fuller et al., 2007; Boivin et al., 2018). Owing to its intensive demands for water/irrigation and associated labour necessities, rice agriculture is hypothesised is to have spread in South Asia, first through ecologically conducive wet zones, and to drier areas only when social complexity and labour control could be manifested (Fuller and Qin 2009). While textual records and archaeological evidence of irrigation features have been seen as evidence of irrigated rice agriculture in the region, recent phytolith and charred macrobotanical data indicate that this link needs to be evaluated with additional lines of evidence (Kingwell-Banham, 2019).

The two regions mentioned in this study not only differ in geography and climate, but also in terms of the trajectories towards early agriculture. We hypothesise, therefore, that these differences should be discernible isotopically. The isotopic signatures of the archaeobotanical remains from Sanganakallu-Kupgal should reflect its semi-arid environment, while those from the East Indian coast should reflect a wetter environment. Moreover, since the all three East Indian sites are synchronous and similar in their archaeology, the isotopic signatures should reflect a similar agroecology for the crop remains. Lastly, Paithan, with its excavated irrigation channels and fully urban nature, is expected to demonstrate farming strategies such as high-yielding, irrigated rice paddies that catered to a larger population compared to the other, earlier sites.

3. Stable carbon and nitrogen isotope analysis of archaeobotanical assemblages: direct insight into farming conditions

Stable isotope analysis of archaeological human and faunal remains is a widely exploited method of exploring aspects such as diet and mobility. However, stable isotope analysis of well-preserved charred archaeobotanical remains to understand agricultural strategies has only been recently used in novel studies in parts of Europe and South-west Asia (e.g., Fraser et al., 2011; Bogaard et al., 2013; Wallace et al., 2013, 2015; Bogaard, 2015; Styring et al., 2016a, 2016b; Bogaard and Arbogast, 2016; Bogaard et al., 2016; Nitsch et al., 2017; Styring et al., 2017), and remains unexplored in South Asia. Reconstructing past agroecologies using stable isotope analysis provides direct evidence of crop growing conditions, and enables us to track changes in agricultural strategies through time and space.

The carbon isotope patterning in living organisms is largely linked to isotopic fractionation associated with the photosynthetic pathway of the plant. In C3 plants such as wheat, rice, barley, and pulses the stable carbon isotope value is influenced by stomatal conductance, which in turn is determined by water status (e.g., Araus et al., 1997; Wallace et al., 2013). C4 plants such as millets and maize are arid-adapted (Sage and Monson, 1999) and therefore their stomatal conductance, and in turn the stable carbon isotope values, are not determined in the same way by water status (e.g., Ellsworth and Cousins, 2016; Lightfoot et al., 2019). Additionally, carbon isotope values can be impacted by salinity, altitude and variety/landrace (e.g., Yousfi et al., 2009; Lightfoot et al., 2019), and the suite of environmental effects can be complicated to fully parse out, especially in archaeobotanical grains where a high number of unknowns exist (Araus et al., 2007, 2013; Wallace et al., 2015; Flohr et al., 2019; Jones et al., 2021).

While deliberate anthropogenic watering cannot be directly distinguished from natural sources of water, we can infer selective watering through comparisons between different species (e.g., Araus et al., 1997; Wallace et al., 2013). The stable carbon isotope values can be expressed as carbon discrimination, or 13C (Farquhar et al., 1989), which takes account of the changes in atmospheric δ13C through time and therefore enables comparison of isotopic data from different time periods (Ferrio et al., 2005).

The stable nitrogen isotope values of crop remains, and specifically grains/seeds, primarily reflect the δ15N value of the soil in which the plant grew. This is influenced by the land use history (Peukert et al., 2012) and can reflect agricultural practices such as manuring (e.g., Fraser et al., 2011; Bogaard et al., 2013; Styring et al., 2016a, 2016b; Nitsch et al., 2017; Styring et al., 2017), while factoring in the effects of environmental constraints such as aridity (e.g., Styring et al., 2016a, 2016b; Styring et al., 2017). Previous studies have shown that intensive manuring can elevate the crop δ15N values by as much as 10‰ and so the δ15N value can provide insights into the intensity of manuring in agricultural practices (e.g., Fraser et al., 2011; Bogaard et al., 2013; Styring et al., 2016a, 2016b; Santana-Sagredo, 2021). Additionally, soil water regimes affect δ15N of plants, with waterlogged soils having elevated values as a result of denitrification (Kendall, 1998). However, as Lim and colleagues (Lim et al., 2015) have shown with rice agriculture, restricted nitrification in a paddy field may result in lower δ15N values compared to rice grown in upland soils. Moreover, nitrogen cycling is a complex environmental process, which can affect crop δ15N values in a number of additional ways (e.g., Nadelhoffer and Fry 1994; Handley et al., 1999; Högberg 1997; Hobbie and Ouimette 2009; Hobbie and Högberg 2012, Szpak 2014; Tashi et al., 2016). Consequently, similar to stable carbon isotope data, the interpretation of stable nitrogen isotope data from archaeobotanical plant remains is limited in providing a complete view of ancient agro-ecological conditions owing to the high number of unknowns about the past.

4. Sites, samples, methods

4.1. Sites and samples

Table 1. Complete details of the archaeological and modern botanical remains analysed in this study. (Attached).

Site	Period	Age (cal. BC estimated median age)	Taxa	d15N (avg)	d15N SD	D13C (avg)	D13C SD
SGK	Post Ashmound/Terminal Occupation/Deccan Initial Megalithic	−1230	Barley	9.3	1.9	16.7	0.65
SGK	Post Ashmound/Terminal Occupation/Deccan Initial Megalithic	−1230	Wheat	12.7	1.5	16.9	0.32
SGK	Post Ashmound/Terminal Occupation/Deccan Initial Megalithic	−1230	Horsegram	3.6	2.6	18.2	0.87
SGK	Ashmound/Deccan Neolithic	−1780	Barley	11.7	0.9	15.2	0.55
SGK	Ashmound/Deccan Neolithic	−1780	Wheat	10.2	0.6	16.9	0.48
SGK	Ashmound/Deccan Neolithic	−1780	Horsegram	3.9	1.4	17.6	0.54
HRP	Eastern Neolithic-Chalcolithic	−1250	Rice	7.3	1.1	18.8	0.68
HRP	Eastern Neolithic-Chalcolithic	−1250	Horsegram	2.2	1.2	18.6	1.20
GPR	Eastern Neolithic-Chalcolithic	−1160	Rice	8.5	1.8	18.8	0.66
GPR	Eastern Neolithic-Chalcolithic	−1160	Horsegram	1.8	0.7	17.5	0.44
GBSN	Eastern Neolithic-Chalcolithic	−1200	Rice	6.1	0.4	19.5	0.54
GBSN	Eastern Neolithic-Chalcolithic	−1200	Horsegram	2.6	0.1	17.1	0.15
PTN	Phase 1 Early Historic	−150	Barley	13.8	2.3	15.9	0.40
PTN	Phase 1 Early Historic	−150	Rice	6.8		19	

PTN	Phase 2 Early Historic	200	Rice	6.3		19.3	
PTN	Phase 3 Early Historic	550	Rice	6.1	1.8	19.5	0.68
PTN	Phase 3 Early Historic	550	Wheat	13.2	1.1	16.5	0.53

4.1.1. East India: Gopalpur, Golbai Sasan and Harirajpur-Bang

The three East Indian sites that form part of this study, Gopalpur, Golbai Sasan and Harirajpur, are all mound settlements with their inhabitants practicing agriculture of domesticated crop (rice and pulses, with small amounts of millets) and animal species (Basa and Mohanty, 2000; Fuller and Harvey, 2006; Harvey et al., 2006; Mohanty et al., 2012). The sites are located in close proximity to each other (Fig. 1), with a distance of 24 km separating Golbai Sassan and Harirajpur, and Gopalpur located 21 km to the west of the former. Additionally, all three sites are roughly contemporaneous, with Gopalpur spanning c.1395-915 BCE, Golbai Sassan spanning c. 1500-900 BCE, and Harirajpur-Bang spanning 1370–1115 BC (Harvey et al., 2006; Kingwell-Banham et al., 2018). A subsample of the archaeobotanical assemblages from all three sites was obtained for stable isotope analysis (refer to Table 1 for details). We also sampled 43 cow/buffalo bone fragments for analysis, but due to extremely poor collagen preservation all the samples failed.

4.1.2. South Deccan: Sanganakallu Kupgal

Several South Deccan sites have been radiocarbon dated, and on the basis of these dates a timeline has been posited (e.g. Fuller et al., 2007; Fuller and Murphy, 2014; Kingwell-Banham et al., 2015; Boivin et al., 2018). The earliest sites from the Southern Neolithic date to c. 3000 BCE and this is termed Southern Neolithic Phase 1a. This is followed by the emergence of the ashmounds and management and herding of cattle and caprines at around 2500 BCE. This is termed the Southern Neolithic Phase 1b. It is only by about 2200 BCE, i.e. Southern Neolithic Phase 2, when village sites such as Sanganakallu-Kupgal appear across the hilltops of the southern peninsula, in proximity to ashmounds, that we see evidence of crop cultivation. In Southern Neolithic Phase 3, which starts at c. 1800 BCE, ashmounds are abandoned, though some hill-top village sites continue to be occupied up to the Megalithic period (c. 1400-1200 BCE). The archaeobotanical remains suggest subsistence based on cultivated millets, pulses, wheat, and barley (Fuller et al., 2004). While there is demographic continuity in the region around the Tungabhadra and Krishna river basins during the transition from Neolithic Phase 3 to the Megalithic period, south of this region in Sanganakallu-Kupgal there is an intensification of settlement and subsistence on the hill-top villages followed by an almost complete abandonment. This has been hypothesised to be due to an increase in aridity (Roberts et al., 2016). Here we consider the contexts spanning this transition, approximately 1750–1000 BC.

4.1.3. North Deccan: Paithan

The second site in the Deccan, Paithan, is located in the northwestern part of the plateau and dates from the Early Historic period to the early Medieval period (c. 300 BCE to 7th century AD). It is roughly 500 km northwest of Sanganakallu-Kupgal (Fig. 1), but nevertheless lies in the same semi-arid geographical region. The extraordinarily rich assemblage of archaeobotanical remains demonstrate the persistence of the Southern Neolithic millet (Fuller et al., 2004; Fuller, 2013), as well as a diversified diet based on rice, wheat, barley, winter pulses, horsegram, and African millets (sorghum, pearl millet, finger millet) (Fuller, 2013). The archaeobotanical analysis by Fuller (2013) suggests that millets were the staple crops, and rice was likely a high-status food. Additionally, there appears to have been successive agricultural diversification and intensification (increasing repeated cropping on the same lands, as well as reducing the fallow season between cropping) through time (Fuller, 2013).

4.2. Methods

4.2.1. Pre-treatment of plant remains

Botanical remains can be charred and preserved as the result of a number of different processes such as roasting, cooking, accidental fire, etc. However, not all charred archaeobotanical remains are suitable for stable isotope analysis. Only well-preserved charred remains which conformed to the experimentally determined "optimal charring window" (Charles et al., 2015; Nitsch et al., 2015) were selected for analysis. Furthermore, charred archaeobotanical remains are susceptible to different kinds of contamination (by carbonates, nitrates, and humic acid) in the soil. In order to remove contamination that can distort the stable isotope values of the cereals, it becomes necessary to carry out pre-treatment. In light of the evidence that harsh acid treatments (which have sometimes been used to remove humic acid contamination) can cause a c. 1‰ decrease in the δ15N values of the material, the pre-treatment strategy outlined by Vaiglova et al. (2014) was adopted. For pre-screening a subset of seeds from each site representing different contexts and taxa was chosen and crushed. The crushed samples were analysed using Fourier Transform Infrared Spectroscopy with Attenuate Total Reflectance (FTIR-ATR): Agilent Technologies (Stockport, UK) Cary 640 FTIR instrument with a GladiATR™ accessory from PIKE Technologies (Madison, WI, USA). The results were compared with the characteristic peaks of the different contaminants (carbonates, nitrates, and humic acid) provided by Vaiglova and colleagues (Vaiglova et al., 2014, Fig. 4, Fig. 5) to assess the levels and type of contamination present. It was observed that no significant contamination was present in samples from any of the sites. In the interest of reducing mass loss, it was therefore decided that no further chemical pre-treatment was necessary. The botanical remains were ground to a powder using an agate mortar and pestle in laboratory conditions as part of pre-treatment.

4.2.2. Stable isotope analysis

Following the pre-treatment, the samples were prepared for analysis by weighing them out into tin capsules. These were then run in a 20/22 continuous flow isotope ratio mass spectrometer coupled to an elemental analyser (Sercon Ltd., Crewe, UK) along with international standards (IAEA-CH6, IAEA-CH7, IAEA-600, and IAEA-N2). The raw isotope data obtained from the analysis was subjected to two-point normalisation against the values obtained for the international standards.

4.2.3. Constructing a modern rice baseline

Charring causes the amino acids and starch in the grain to undergo Maillard reactions, thereby resulting in the formation of heterocyclic aromatic, cross-linked products and high molecular weight melanoidins (Knicker et al., 1996; Silván et al., 2006; Styring et al., 2013) which are resistant to microbial attack and therefore enable the grain to survive archaeologically (Braadbaart et al., 2004a, 2004b; Ascough et al., 2010; Charles et al., 2015). However, these processes which enable the preservation of the grains may also cause a change in the stable carbon and nitrogen isotope ratios. Since the utility of stable isotope analysis of plant remains relies on the ability to arrive at the original values of the uncharred grain, it becomes necessary to determine this offset accurately. The offset for wheat and barley (calculated by Nitsch et al., 2015) was accounted for, but no such offset was available in the literature for rice. To this effect, using the method outlined by Nitsch and colleagues

(Nitsch et al., 2015) the offset caused in the δ13C and δ15N values of well-preserved grains was constructed by conducting charring experiments on two varieties of irrigated Indian rice – Sonamasuri and Manaswini. These two varieties were chosen because they are widely grown, well-researched, and local to the two regions under study. Both samples were obtained from fields under organic cultivation, with minimal manuring.

5. Results

5.1. Experimentally charred modern rice

Two varieties of irrigated Indian rice, one from East India, and one from the South Deccan, were experimentally charred and analysed. The δ13C values of the uncharred East Indian rice samples ranged from −26.9 to −27.2‰, while the experimentally charred samples ranged from −26.3 to −26.9‰. The δ15N values ranged from 2.9 to 3.0‰ for the uncharred samples, and was 3.5‰ for the charred samples. For the South Deccan rice variety, the δ13C values of the uncharred samples ranged from −26.2 to −26.3‰ and of those of the charred samples ranged from −25.5 to −26.0‰. The δ15N values of the uncharred samples varied from 3.8 to 4.7‰, and those of the charred samples from 3.8 to 4.7‰ (See Table 1 for full details). The offset caused by charring was calculated to be +0.58‰ for δ15N and +0.62‰ for δ13C for the East Indian rice. In the case of the South Deccan rice, the δ13C charring offset was calculated to be +0.44‰ and that for δ15N was −0.02‰. We applied the average offset of 0.28‰ for δ15N and 0.53‰ for δ13C to our archaeobotanical rice remains to account for the effects of charring. All δ13C values were converted to Δ13C (using the method put forward by Farquhar et al. (1989)) to enable comparison with the archaeobotanical data presented below.

5.2. Golbai Sasan

The δ13C values of the rice from this site ranged from −24.8 to −25.9‰. The δ13C values were converted to Δ13C (Farquhar et al., 1989) and these values varied between 18.8 and 20.0‰. The δ15N values ranged from 5.4 to 6.5‰. The average Δ13C value was 19.5‰ (standard deviation = 0.5‰), and the average δ15N value 6.1‰ (standard deviation = 0.4‰). Additionally, while it was not possible to formulate a water status framework for rice, the high Δ13C values are consistent with the 'well-watered' modern rice samples. Coupled with this, the high δ15N values are consistent with cultivation in rainfed fields of coastal Odisha, with the possible input of manure.

5.3. Gopalpur

The δ13C values of the rice from this site ranged from −25.7 to −24.1‰. The δ13C values were converted to Δ13C (Farquhar et al., 1989) and these values varied between 18.1 and 19.7‰. The δ15N values ranged from 5.3 to 9.8‰. The average Δ13C value was 18.8‰ (standard deviation = 0.7‰), and the average δ15N value 8.5‰ (standard deviation = 1.8‰). One sample from Gopalpur, GPR05, was a clear outlier, with a much lower δ15N value of 5.3‰.

The Δ13C values demonstrate similarly high values to those observed in Golbai-Sasan and are consistent with a 'well-watered' management. The δ15N values are again high, but they are (excluding the outlier) c. 3‰ higher than those observed in Golbai Sasan and c. 2‰ higher than those in Harirajpur-Bang.

5.4. Harirajpur-Bang

The δ13C values of the rice from this site ranged from −26.0 to −24.1‰. The δ13C values were converted to Δ13C (Farquhar et al., 1989) and these values varied between 18.0 and 20.1‰. The δ15N values ranged from 6.0 to 9.1‰. The average Δ13C value was 18.8‰ (standard deviation = 0.7‰), and the average δ15N value was 7.3‰ (standard deviation = 1.1‰). The high Δ13C values of the rice grains are consistent with the 'well-watered' management strategy.

The δ13C values of the horse gram from this site ranged from −26.2 to −24.9‰. The Δ13C values varied between 18.9 and 20.3‰. The δ15N values ranged from 0.9 to 2.0‰. The average Δ13C value was 19.5‰ (standard deviation = 0.7‰), and the average δ15N value was 1.6‰ (standard deviation = 0.6‰). According to the framework outlined by Wallace et al. (2013), these horsegram grains fall comfortably within 'well-watered' status for pulses. Horsegram, as a pulse, is a nitrogen-fixer and the data conform to the values expected for zero to minimal manuring. The similarity in the Δ13C values of the plant remains from this site point towards the high water availability during growth.

5.5. Sanganakallu-Kupgal

The δ13C values of the horsegram from this site ranged from −24.8 to −22.9‰, the Δ13C values from 16.9 to 18.9‰, and the δ15N values from 1.2 to 6.6‰. The average Δ13C value was 17.9‰ (standard deviation = 0.8‰), and the average δ15N value was 3.7‰ (standard deviation = 2.0‰). The δ13C values of the barley from this site ranged from −23.2 to −20.9‰, the Δ13C values from 14.8 to 17.2‰, and the δ15N values from 7.9 to 12.6‰. The average Δ13C value was 15.9‰ (standard deviation = 1‰), and the average δ15N value was 10.5‰ (standard deviation = 1.9‰). The δ13C values of the wheat from this site ranged from −23.4 to −22.7‰, the Δ13C values from 16.3 to 17.4‰, and the δ15N values from 9.7 to 13.7‰. The average Δ13C value was 16.9‰ (standard deviation = 0.4‰), and the average δ15N value was 11.0‰ (standard deviation = 1.5‰).

According to the framework outlined by Wallace and colleagues (Wallace et al., 2013), the horsegram from the site falls within the well-watered range, the wheat within the moderate-to well-watered range, while the barley falls within the poorly watered range. Additionally, the high δ15N values for all three crops likely reflect the effects of aridity, as well as of manuring.

5.6. Paithan

The δ13C values of the wheat from this site ranged from −22.8 to −22.3‰, the Δ13C values from 16.3 to 16.8‰, and the δ15N values from 11.6 to 14.9‰. The average Δ13C value was 16.5‰ (standard deviation = 0.4‰), and the average δ15N value was 13.2‰ (standard deviation = 2.3‰). The δ13C values of the barley from this site ranged from −22.7 to −21.2‰, the Δ13C values from 15.2 to 16.8‰, and the δ15N values from 12.6 to 16.5‰. The average Δ13C value was 15.9‰ (standard deviation = 0.7‰), and the average δ15N value was 13.9‰ (standard deviation = 1.8‰). The δ13C values of the rice from this site ranged from −25.6 to −24.5‰, the Δ13C values from 18.6 to 19.8‰, and the δ15N values from 5.4 to 7.9‰. The average Δ13C value was 19.1‰ (standard deviation = 0.5‰), and the average δ15N value was 6.6‰ (standard deviation = 0.9‰).

Wallace and colleagues' (Wallace et al., 2013) framework suggests that the wheat from Paithan is moderately watered, while the barley is poorly watered. The Δ13C values of the rice are similar to those of modern well-irrigated rice and this is likely an indication of it being well-watered. The stable nitrogen isotope values of all crops from this site are very high, and suggest intensive manuring.

6. Discussion

6.1. Irrigation and early agricultural experimentation

The results from this study demonstrate direct evidence of agricultural variability in Indian prehistory, and the increasing agricultural input from the Neolithic-Chalcolithic to the Early Historic. The rice assemblages in this study allow for a more nuanced view of the changing agricultural practices. The results demonstrate that the rice from Early Historic Paithan is similar in its water status to the irrigated modern rice samples from the region. On the other hand, while the archaeological rice from the East Indian Neolithic-Chalcolithic sites overlaps or is similar to that from Paithan, it is in a wetter region of India. Moreover, it has higher δ13C values than the modern, irrigated rice from the region. Experimental studies have shown that rice grown in paddyfields have lower δ15N values compared to upland rice as a result of restricted nitrification (Lim et al., 2015). The archaeological rice from Paithan and the East Indian sites are all elevated in δ15N compared to the modern irrigated rice samples. However, the δ15N values of the rice from Gopalpur and Harirajpur-Bang are the most elevated, while those from Golbai Sassan and Paithan are lower (see Fig. 2).

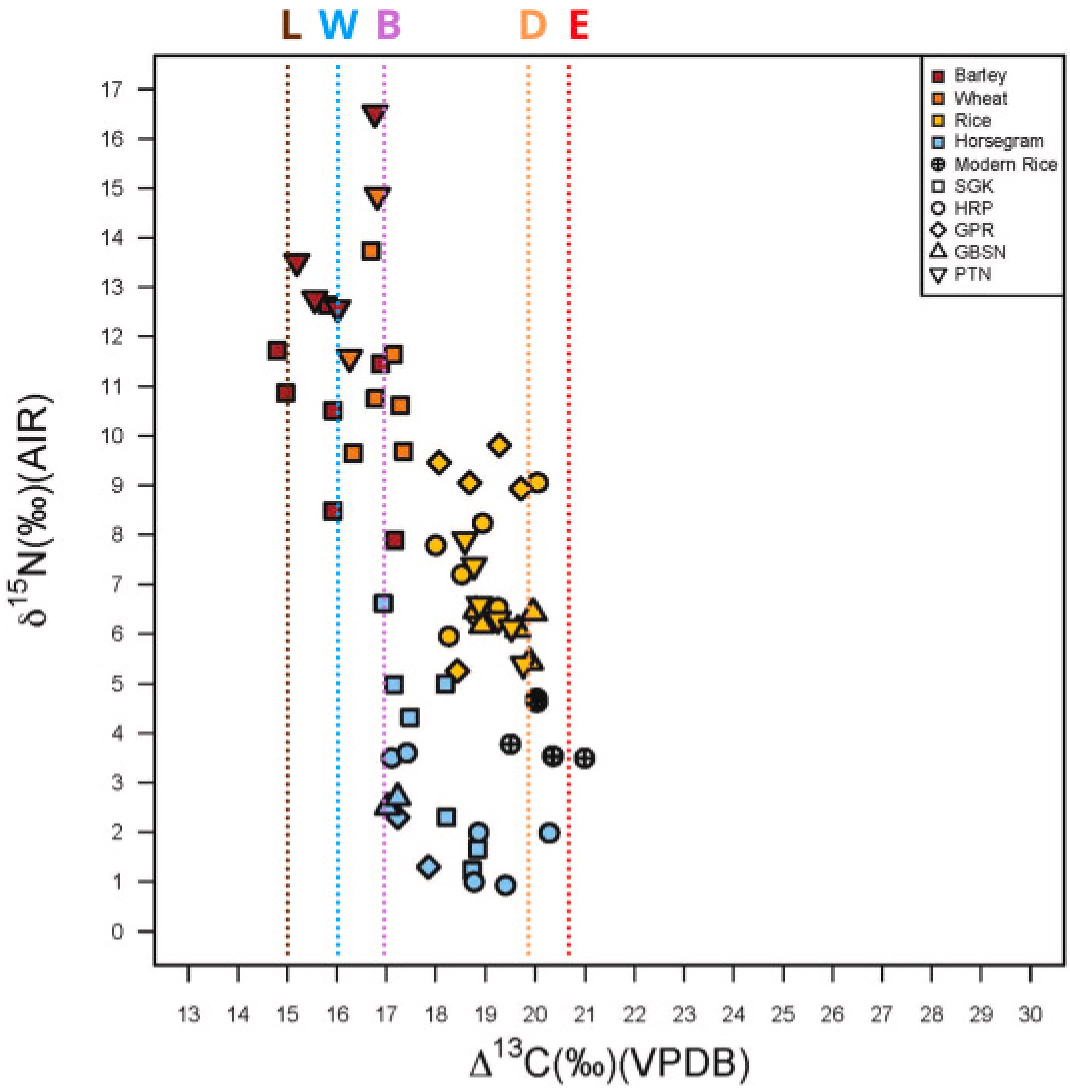

Fig. 2. Archaeobotanical and modern Δ13C and δ15N values colour-coded by taxon. The dotted lines labelled 'L', 'W', and 'B' represent the 'poorly watered' threshold for lentil, wheat and barley respectively, as determined by Wallace et al., (2013). The dotted lines labelled 'D' and 'E' indicate the average reference values obtained from the experimentally charred modern Deccan and Eastern rice respectively that were analysed as part of this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The δ13C and δ15N values of the archaeological rice assemblages allow us a nuanced view of past agricultural practices. In the East Indian Neolithic-Chalcolithic, the archaeological rice shows a high variability. These sites span the earliest stage of agriculture in the region (Kingwell-Banham et al., 2018). The results in this study indicate that in this early phase, cultivation was highly experimental. The elevated δ15N values, relative to the modern, irrigated and minimally manured rice from the region, coupled with the higher δ13C values points towards rainfed cultivation with varying intensity of manure. At Paithan, located in the semi-arid savannah region, the archaeological δ13C data is similar to the modern, but the average δ15N is higher than the modern. Dry savannah conditions were established in the north Deccan by c. 3000 BC and close to modern conditions from around 2000 years ago (Prasad et al., 2014; Giosan et al., 2017). This is significant as the typical precipitation in the region is insufficient for reliable rainfed dry rice cultivation. It has therefore been inferred that the dispersal of rice throughout the Deccan occurred only once irrigated wet rice systems had been developed, with possible origins in the Odisha region (Fuller and Qin, 2009; Fuller et al., 2011). Despite being in a drier zone, the rice from Paithan does not look drier than the rice from the East Indian sites and looks similar in wetness to the modern irrigated samples from the same region. The stable isotope data coupled with the evidence of irrigation channels at the site (Kennet et al., 2013) indicates that Paithan shows evidence of irrigation and manuring. This confirms that the establishment of rice in the Deccan required both watering and social readiness to invest the requisite labour (Fuller and Qin, 2009; Fuller et al., 2011).

The data from the archaeological wheat and barley from Paithan further attest to agricultural management in the form of irrigation and manuring. The presence of both winter and summer crops at the site points towards double cropping. Therefore, the wheat and barley would have been cultivated in the rabi or post-monsoon, dry winter season. The δ13C results indicate preferential watering of wheat, while the barley is poorly watered. Barley is better adapted to arid environments and within the dry conditions of the north Deccan, it is apparent that the farmers at Paithan carefully managed and directed their water resources towards crops requiring more irrigation. Such management would have been possible only with an understanding of the crop water requirements and control of resources to enable year-round agriculture in a semi-arid region. The extremely elevated δ15N values of the wheat and barley corroborate the intensity of manuring and, by extension, of labour at this site. While elevated δ15N values can be a reflection of aridity, the stable carbon isotopes data from the site confirms the availability of well-watered fields. Moreover, comparison with modern data from similar, dry environments (Styring et al., 2016a, 2016b, 2017) demonstrates that the extremely high δ15N values of the wheat and barley at this site are as a result of high levels of manuring. Therefore, the archaeological crop isotope data from Paithan bears testimony to the high input, highly managed agricultural practices during the Early Historic in the north Deccan.

Section 6.2 Isotopic and cultural evidence of diversified dung use.

Additionally, the horsegram data from the East Indian sites and Sanganakallu-Kupgal demonstrates the differences in agricultural management (Fig. 3). Horsegram is a summer monsoon crop that is highly drought resistant. While the δ13C values show that the horsegram from Sanganakallu-Kupgal and the East Indian sites grew under varied watering regimes, the δ15N values are higher for the former. There are two possible reasons for this: first, that the crops at Sanganakallu-Kupgal were manured much more; and/or secondly, that the elevated stable nitrogen values at Sanganakallu-Kupgal are the result of greater aridity. As a nitrogen-fixing plant, unmanaged horsegram has low δ15N values, usually 0–2‰ (e.g., (Treasure et al., 2016; Styring et al., 2017). The East Indian horsegram samples appear to have received little to no manuring. The horsegram data from Sanganakallu-Kupgal shows that the high δ15N and Δ13C throughout Ashmound and Post-Ashmound phases point to high water availability and manuring (Fig. 4, Fig. 5). At Sanganakallu-Kupgal, the wheat and barley samples also have δ15N values consistent with high levels of manuring (e.g., Styring et al., 2016a, 2016b). This site, like other Southern Neolithic sites, demonstrates significant engagement of its occupants with cattle dung, with burnt layers of it present across much of the site.

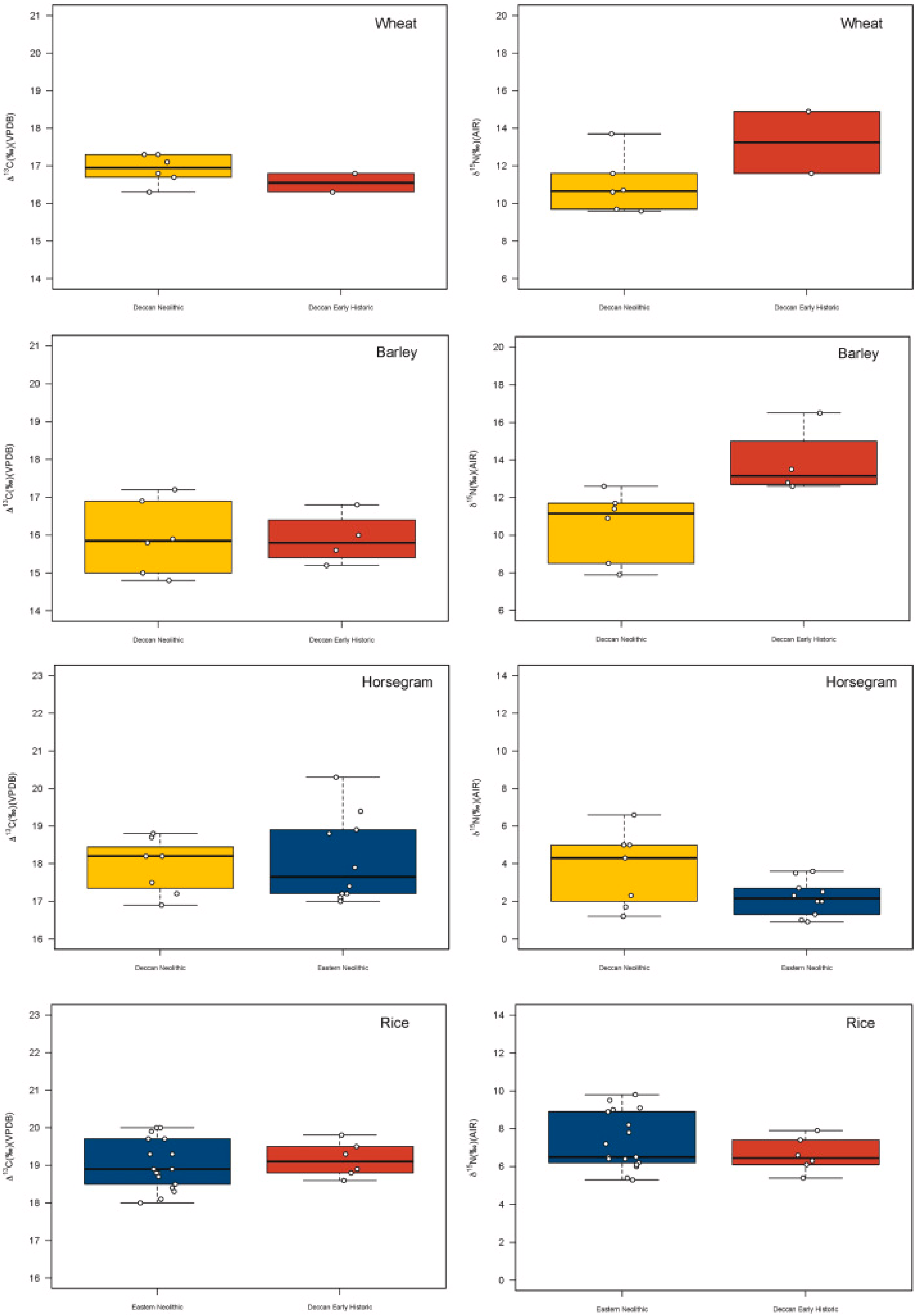

Fig. 3. Δ13C and δ15N values for each taxon separated into box plots by period.

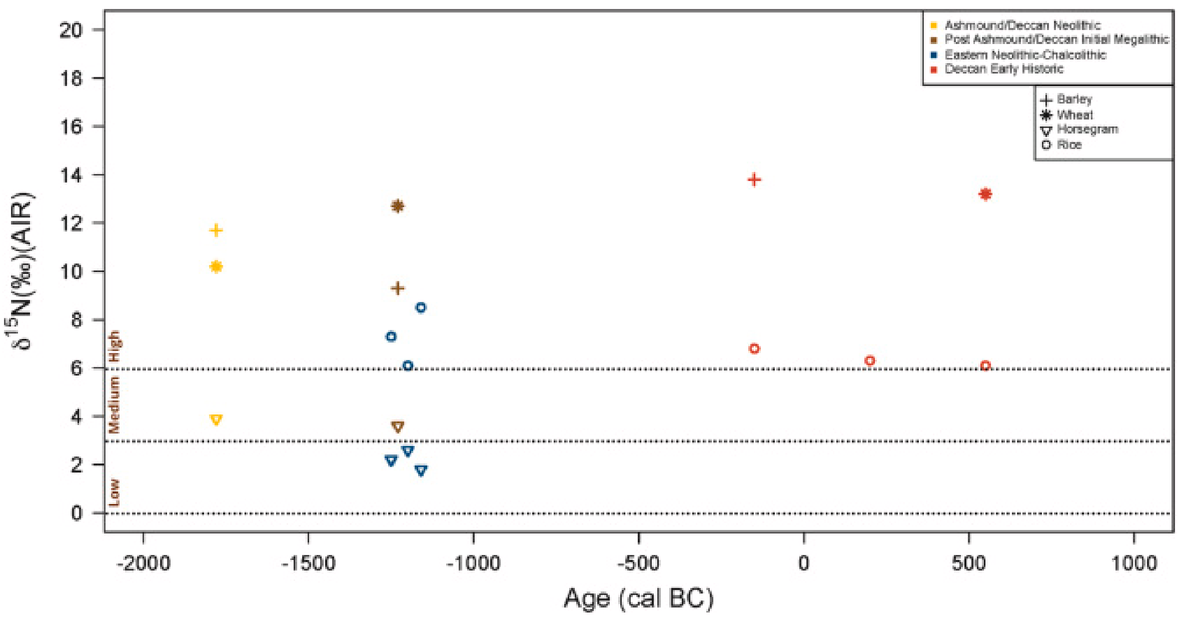

Fig. 4. Average δ15N values of archaeobotanical samples plotted through time. The dotted lines refer to thresholds of low, medium, and high manuring in cereals as reported in Bogaard et al., (2013).

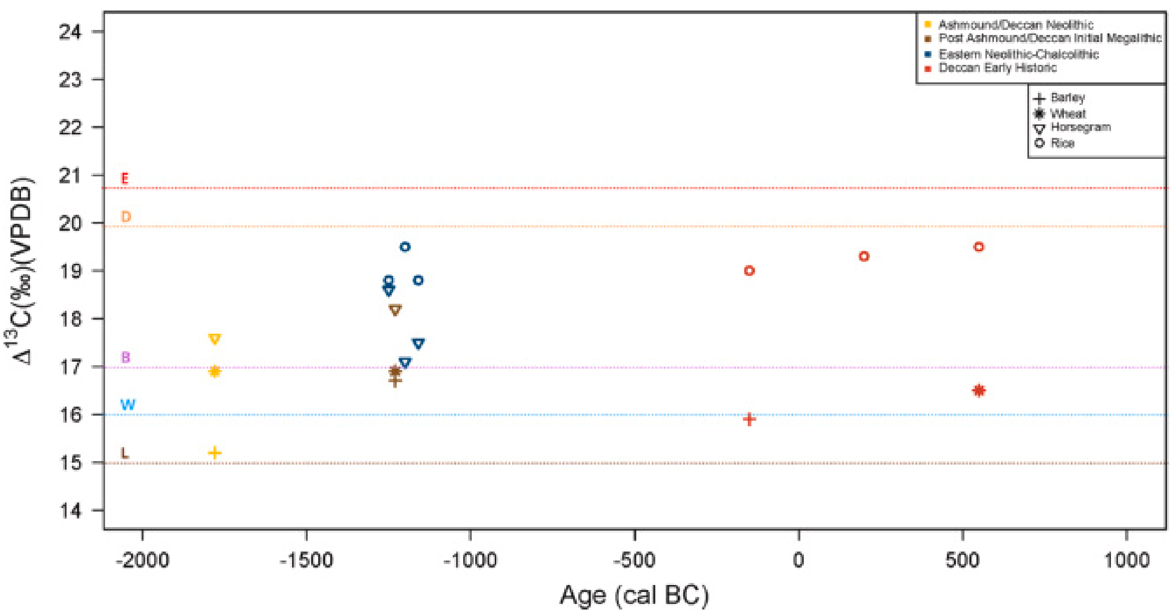

Fig. 5. Average Δ13C values of archaeobotanical samples plotted through time. The dotted lines follow the schematic from Fig. 2, i.e., 'L', 'W', and 'B' represent the 'poorly watered' threshold for lentil, wheat and barley respectively, as determined by Wallace et al., (2013), and those labelled 'D' and 'E' indicate the average reference values obtained from the experimentally charred modern Deccan and Eastern rice.

Interestingly, in later phases of Sanganakallu-Kupgal (c. 1700–1600 BC), burning of cattle dung appears to cease or at least be significantly reduced (Roberts et al., 2016). While this doubtless reflects some changes in ritual activities, it also correlated with increased sedentism, crop diversification and the inferences of more intensive agricultural practices (Fuller et al., 2001). The general decline of ashmound formation during the 2nd millennium BC has been suggested to correlate with increased use of dung as an agricultural resource (Fuller et al., 2001: 184), and this hypothesis is given its first empirical support from our isotopic data. This is a fascinating hypothesis that holds implications for how we understand the shift during the course of the southern Neolithic away from the ritualised burning of animal dung, with the ashmound formation largely confined to phases I and II, declining from IIIA onwards. The enigmatic ashmounds of the southern Indian Neolithic have long fascinated scholars, and clues as to why the practices that created them were abandoned have been elusive (Foote, 1887; Subbarao, 1948; Allchin, 1963; Mujumdar and Rajaguru, 1966; Sundara, 1987; Paddayya, 1991, 1993, 2000; Fuller, 2000; Korisettar et al., 2001a, 2001b; Boivin et al., 2005). That animal dung was increasingly recognised as a resource is evident from the data presented here, and should be considered one of the contributing causes.

7. Conclusions and future prospects

Isotopic studies have been rarely applied to South Asian archaeology. The present study is the first cross-temporal, multi-site, multi-species stable isotope dataset from archaeobotanical remains for the region, and is thus an important contribution. Our results demonstrate clear patterning in crop isotopic data that is consistent with environmental and climatic variability, but also suggests some differences that, where isotopic patterns do not conform to regional climate patterns, can be attributed to agricultural management. In particular, we find evidence that wheat and rice were both likely irrigated, or at least preferentially watered, i n the dry environment of the Deccan sites. In addition, rice, which was grown under naturally wet conditions in the Neolithic-Chalcolithic period in East India, appears to have been irrigated at Early Historic Paithan. This confirms the importance of wet rice cultivation systems in fostering the dispersal of rice throughout the arid Deccan region. The study also provides new insights into agricultural practices across all the regions investigated, suggesting the value of direct stable isotope evidence from archaeological grains. In the case of South Indian wheat, barley and horsegram cultivation, the use of manure in agriculture can be seen as a factor that worked against the continued use of dung non-utilitarian rituals that produced ashmounds.

Overall our results, while preliminary, highlight the role for stable isotopes from archaeological remains as evidence to support or develop hypotheses regarding practices of irrigation or manuring. Our results suggest that in Neolithic-Chalcolithic Odisha, rice was grown under rainfed conditions rather than in paddy fields at this early stage of agriculture in this region of India. This is in line with previous hypotheses about the spread of rice agriculture being facilitated through wet, conducive environments and not adaptations to new conditions. However, the high amount of variability attests to the experimental nature of early farming communities in Neolithic-Chalcolithic Odisha. At Sanganakallu-Kupgal, the trend in the data hints at changing agricultural strategies that are cogent with the changes observed in the landscape and material culture of South India. In the increasingly climatically tenuous post-ashmound phase, we see an innovative use of the vitrified ash as manure to facilitate the sedentary cultivation of crops in a semi-arid region. Lastly, at Early Historic Paithan, the crop stable isotope data shows intensified cultivation with an irrigation and manuring regime. These results call for comparative baseline studies on modern crops grown under known conditions, as well as increased isotopic sampling of archaeological plant remains.

Acknowledgements

The authors are grateful to the Archaeological Survey of India, particularly to the erstwhile Director-General, Dr. Rakesh Tewari, for permission to export and analyse the samples mentioned in this study. AN, NB and PR are grateful to the Max Planck Society for funding and support. AN thanks the School of Archaeology (University of Oxford), the Research Laboratory for Archaeology and the History of Art (University of Oxford), St. Peter's College (University of Oxford), Utkal University, and Deccan College Post-Graduate and Research Institute for support and/or funding.

References

Allchin, B.G., Allchin, B., Allchin, R., 1982. *The Rise of Civilization in India and Pakistan*. Cambridge University Press.

Allchin, F.R., 1963. *Neolithic Cattle-Keepers of South India: A Study of the Deccan Ashmounds*. CUP Archive.

Ammerman, A.J., Cavalli-Sforza, L.L., 1971. Measuring the rate of spread of early farming in Europe. *Man* 6 (4), 674–688.

Araus, J.L., Febrero, A., Buxo´, R., Rodrıǵ uez-Ariza, M.O., Molina, F., Camalich, M.D., Martıń , D., Voltas, J., 1997. Identification of ancient irrigation practices based on the carbon isotope discrimination of plant seeds: a case study from the south-East Iberian peninsula. *J. Archaeol. Sci*. 24 (8), 729–740.

Araus, J.L., Ferrio, J.P., Bux´o, R., Voltas, J., 2007. The historical perspective of dryland agriculture: lessons learned from 10,000 years of wheat cultivation. *J. Exp. Bot*. 58, 131–145.

Araus, J.L., Ferrio, J.P., Voltas, J., Aguilera and, M., Bux´o, R., 2013. Agronomic conditions and crop evolution in ancient Near East agriculture. *Nat. Commun.* 5, 3953.

Ascough, P.L., Bird, M.I., Scott, A.C., Collinson, M.E., Cohen-Ofri, I., Snape, C.E., Le Manquais, K., 2010. Charcoal reflectance measurements: implications for structural characterization and assessment of diagenetic alteration. *J. Archaeol. Sci.* 37 (7), 1590–1599.

Basa, K.K., Mohanty, P. (Eds.), 2000. *Archaeology of Orissa, vol. I.* Pratibha Prakashan.

Bellwood, P., 2004. *First Farmers: the Origins of Agricultural Societies.* Wiley.

Bellwood, P.S., Renfrew, C., 2003. *Examining the Farming/language Dispersal Hypothesis*. McDonald Institute for Archaeological Research.

Bogaard, A., 2015. New insights into early farming practice and diet from stable isotope analysis of crop assemblages. In: *Neolithic Diversities: Perspectives from a Conference in Lund, Sweden*. Acta Archaeologica Lundensia, 8, pp. 33–42.

Bogaard, A., Arbogast, R.M., 2016. The Bandkeramik settlement of Vaihingen an der Enz, Kreis Ludwigsburg (Baden-Württemberg): an integrated perspective on land use, economy and diet. Germania. https://journals.ub.uni-heidelberg.de/index.php/germania/article/view/39068.

Bogaard, A., Fraser, R., Heaton, T.H.E., 2013. Crop manuring and intensive land management by Europe's first farmers. *Proc. Natl. Acad. Sc*i. https://www.pnas.org/ content/110/31/12589.short.

Bogaard, A., Hodgson, J., Nitsch, E., Jones, G., Styring, A., Diffey, C., Pouncett, J., Herbig, C., Charles, M., Ertug, F., Tugay, O., Filipovic, D., Fraser, R., 2016. Combining functional weed ecology and crop stable isotope ratios to identify cultivation intensity: a comparison of cereal production regimes in Haute Provence, France and Asturias, Spain. *Veg. Hist. Archaeobotany* 25, 57–73.

Boivin, N.L., Fuller, D.Q., Korisettar, R., Nayak, A., Petraglia, M.D., 2018. The emergence of agriculture and pastoralism in the northern Maidan region of South Deccan, south India. In: *Beyond Stones and More Stones*. The Mythic Society, pp. 95–126.

Boivin, N.L., Korisettar, R., Fuller, D., 2005. Further research on the southern neolithic and the ashmound tradition: the Sanganakallu-Kupgal archaeological research project interim report. J. *Interdiscipl. Stud. Hist. Archaeol.* 2 (1), 63–92.

Braadbaart, F., Boon, J.J., Veld, H., David, P., van Bergen, P.F., 2004a. Laboratory simulations of the transformation of peas as a result of heat treatment: changes of the physical and chemical properties. J. Archaeol. Sci. 31 (6), 821–833.

Braadbaart, F., van der Horst, J., Boon, J.J., van Bergen, P.F., 2004b. Laboratory simulations of the transformation of emmer wheat as a result of heating. *J. Therm. Anal. Calorim.* 77 (3), 957–973.

Charles, M., Forster, E., Wallace, M., Jones, G., 2015. Nor ever lightning char thy grain: establishing archaeologically relevant charring conditions and their effect on glume wheat grain morphology. *STAR: Sci. Technol. Archaeol. Res.* 1 (1), 1–6.

Childe, V.G., 1936. *Man Makes Himself* London. Watts and Company.

Ellsworth, P.Z., Cousins, A.B., 2016. Carbon isotopes and water use efficiency in C4 plants. *Curr. Opin. Plant Biol.* 31, 155–161.

Eliazer Nelson, Ann Raeboline Lincy, Ravichandran, Kavitha, Antony, Usha, 2019. The impact of the Green Revolution on indigenous crops of India. *J. Ethn. Foods* 6 (1). https://doi.org/10.1186/s42779-019-0011-9.

Farquhar, G.D., Ehleringer, J.R., Hubick, K.T., 1989. Carbon isotope discrimination and photosynthesis. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* 40 (1), 503–537.

Ferrio, J.P., Araus, J.L., Bux´o, R., Voltas, J., Bort, J., 2005. Water management practices and climate in ancient agriculture: inferences from the stable isotope composition of archaeobotanical remains. *Veg. Hist. Archaeobotany* 14 (4), 510–517.

Foote, R.B., 1887. Notes on some recent neolithic and palaeolithic finds in South India. *J. Asiat. Soc. Bengal* 46 (2), 259–282.

Fraser, R.A., Bogaard, A., Heaton, T., Charles, M., 2011. Manuring and stable nitrogen isotope ratios in cereals and pulses: towards a new archaeobotanical approach to the inference of land use and dietary practices. *J. Health.com.* https://www.sciencedirect.com/science/article/pii/S0305440311002226.

Fuller, D., 2000. Ashmounds and hilltop villages: the search for early agriculture insouthern India. *Archaeol. Int. 4.* https://ai-journal.com/article/view/164/.

Fuller, D., Korisettar, R., Venkatasubbaiah, P.C., Jones, M.K., 2004. Early plant domestications in southern India: some preliminary archaeobotanical results. *Veg. Hist. Archaeobotany* 13 (2), 115–129.

Fuller, D.Q., 2003a. African crops in prehistoric South Asia: a critical review. In: Neumann, K., Bulter, A., Kahleber, S. (Eds.), Food , Fuel and Fields . *Progress in Africa Archaeobotany*. Heinrich-Barth-Institut, pp. 239–271.

Fuller, D.Q., 2003b. An agricultural perspective on Dravidian historical linguistics: archaeological crop packages, livestock and Dravidian crop vocabulary. In: Bellwood, P. and Renfrew, C. (eds.) *Examining the Farming/Language Dispersal Hypothesis.* McDonald Institute for Archaeological Research, Cambridge, pp. 191–213.

Fuller, D.Q., 2003c. Indus and non-Indus agricultural traditions: local developments and crop adoptions on the Indian Peninsula. In: Weber, S.A., Belcher, W.R. (Eds.), *Indus Ethnobiology: New Perspectives from the Field*. Lexington Books, pp. 343–396.

Fuller, D.Q., 2006a. Dung Mounds and Domesticators: Early Cultivation and Pastoralism in Karnataka. South Asian Archaeology. http://www.homepages.ucl.ac.uk/~tcrndfu/articles/EASAA2001a.pdf.

Fuller, D.Q., 2006b. Agricultural origins and frontiers in South Asia: a working synthesis. *J. World PreHistory* 20 (1), 1–86.

Fuller, D.Q., 2011. Finding plant domestication in the Indian subcontinent. *Curr. Anthropol.* 52 (S4), S347–S362.

Fuller, D.Q., 2013. Archaeobotany. In: Kennet, D., Varaprasada Rao, J., Kasturi Bai, M. (Eds.), *Excavations at Paithan, Maharashtra: Transformations in Early Historic and Early Medieval India.* Memoirs of the Archaeological Survey of India, pp. 289–328.

Fuller, D.Q., Boivin, N., Korisettar, R., 2007. Dating the Neolithic of South India: new radiometric evidence for key economic, social and ritual transformations. *Antiquity* 81 (313), 755–778.

Flohr, Pascal, Jenkins, Emma, Williams, Helen R.S., Jamjoum, Khalil, Nuimat, Sameeh, Müldner, Gundula, 2019. What can crop stable isotopes ever do for us? An experimental perspective on using cereal carbon stable isotope values for reconstructing water availability in semi-arid and arid environments. *Veg. Hist. Archaeobotany* 28 (5). https://doi.org/10.1007/s00334-018-0708-5.

Fuller, D.Q., Harvey, E.L., 2006. The archaeobotany of Indian pulses: identification, processing and evidence for cultivation. *Environ. Archaeol.* 11 (2), 219–246.

Fuller, D.Q., Korisettar, R., Venkatasubbaiah, P.C., 2001. Southern neolithic cultivation systems: a reconstruction based on archaeobotanical evidence. *S. Asian Stud.* 17 (1), 171–187.

Fuller, D.Q., Murphy, C., 2014. Overlooked but not forgotten: India as A center for agricultural domestication. *Gen. Anthropol.* 21 (2), 1–8.

Fuller, D.Q., Qin, L., 2009. Water management and labour in the origins and dispersal of Asian rice. *World Archaeol.* 41 (1), 88–111.

Fuller, D.Q., van Etten, J., Manning, K., Castillo, C., Kingwell-Banham, E., Weisskopf, A., Qin, L., Sato, Y.-I., Hijmans, R.J., 2011. The contribution of rice agriculture and livestock pastoralism to prehistoric methane levels: an archaeological assessment. *Holocene* 21 (5), 743–759.

Giosan, L., Ponton, C., Usman, M., Glusztajn, J., Fuller, D.Q., Galy, V., Haghipour, N., Johnson, J.E., McIntyre, C., Wacker, L., Others, 2017. Massive erosion in monsoonal central India linked to late Holocene land cover degradation. *Earth Surf. Dyn.* https://scholars.unh.edu/cgi/viewcontent.cgi?article=1514&context=faculty_pubs.

Guhathakurta, Pulak, Kulkarni, Deepa, Khedikar, Shirish, Menon, Preetha, Prasad, Ashwini Kumar, Sable, S.T., Advani, S.C., 2020a. Observed Rainfall Variability and Changes over Odisha State. *Met Monograph: Rainfall Variability* 20.

Guhathakurta, Pulak, Khedikar, Shirish, Menon, Preetha, Prasad, Ashwini Kumar, Sable, S.T., Advani, S.C., 2020b. Observed Rainfall Variability and Changes over Maharashtra State. *Met Monograph: Rainfall Variability* 16 (40).

Guhathakurta, Pulak, Sanap, Shakharam, Menon, Preetha, Prasad, Ashwini Kumar, Sable, S.T., Advani, S.C., 2020c. Observed Rainfall Variability and Changes over Karnataka State. *Met Monograph: Rainfall Variability* 13 (37).

Handley, L.L., Austin, A.T., Stewart, G.R., Robinson, D., Scrimgeour, C.M., Raven, J.A., et al., 1999. The 15N natural abundance (δ15N) of ecosystem samples reflects measures of water availability. *Aust. J. Plant Physiol*. 26, 185–199. https://doi.org/10.1071/PP98146.

Harvey, E.L., Fuller, D.Q., Mohanty, R.K., 2006. Early Agriculture in Orissa: Some Archaeobotanical Results and Field Observations on the Neolithic. *Man and Environment* http://www.homepages.ucl.ac.uk/~tcrndfu/articles/Harveyetal06.pdf.

Hogberg, P., 1997. Tansley Review No. 95. 15N natural abundance in soil-plant systems. *New Phytol.* 137, 179–203. https://doi.org/10.1046/j.1469-8137.1997.00808.x.

Hobbie, E., Ouimette, A., 2009. Controls of nitrogen isotope patterns in soil profiles. *Biogeochemistry* 95, 355–371. https://doi.org/10.1007/s10533-009-9328-6.

Hobbie, E.A., H¨ogberg, P., 2012. Nitrogen isotopes link mycorrhizal fungi and plants to nitrogen dynamics. *New Phytol*. 196 , 367–382. https://doi.org/10.1111/j.1469-8137.2012.04300.x.

India Meteorological Department, 2012. *Rainfall Atlas of India*. India Meteorological Department, Department of Earth Sciences, Government of India.

Jones, P.J., Petrie, C.A., O'Connell, T.C., Jones, M.K., 2019. Investigating adaptation to climate change in the archaeological record: a conceptual framework and an isotopic approach in the Indus Civilisation. In: Myrdal, E. (Ed.), *South Asian Archaeology 2014*. Dev Publishers, Delhi, pp. 1–15.

Kajale, M.D., 1991. Current Status of Indian Palaeoethnobotany: Introduced andIndigenous Food Plants with a Discussion of the Historical and Evolutionary Development of Indian Agriculture and Agricultural Systems in General. *New Light on Early Farming*. Edinburgh University Press, Edinburgh, pp. 155–189.

Kar, Sushanta Kumar, Basa, Kishor K., Joglekar, P.P., 1998. Explorations at Gopalpur, District Nayagarh, Coastal Orissa. *Man Environ*. 23 (1).

Kendall, C., 1998. Chapter 16 - tracing nitrogen sources and cycling in catchments. In: Kendall, C., McDONNELL, J.J. (Eds.), *Isotope Tracers in Catchment Hydrology*. Elsevier, pp. 519–576.

Kennet, D., Rao, J.V., Bai, M.K., Museum, B., & (erc), E. R. C., 2013. *Excavations at Paithan*, Maharashtra. De Gruyter.

Kingwell-Banham, E., Harvey, E., Mohanty, R., Fuller, D., 2018. Archaeobotanical investigations into Golbai Sasan and Gopalpur, two neolithic-chalcolithic settlements of Odisha. *Ancient Asia* 9, 1–14.

Kingwell-Banham, Eleanor, 2019. Dry, rainfed or irrigated? Reevaluating the role and development of rice agriculture in Iron Age-Early Historic South India using archaeobotanical approaches. *Archaeol. Anthropol. Sci.* 11 (12), 6485–6500.

Kingwell-Banham, E., Petrie, C.A., Fuller, D.Q., 2015. Early agriculture in South Asia. In: Barker, G., Goucher, C., Barker, G., Goucher, C. (Eds.), *The Cambridge World History*. Cambridge University Press, pp. 261–288.

Knicker, H., Almendros, G., Gonz´alez-Vila, F.J., Martin, F., Lüdemann, H.-D., 1996. 13C and 15N-NMR spectroscopic examination of the transformation of organic nitrogen in plant biomass during thermal treatment. *Soil Biol. Biochem.* 28 (8), 1053–1060.

Korisettar, R., Joglekar, P.P., Fuller, D.Q., Venkatasubbaiah, P., 2001a. Archaeological Re-investigation and archaeozoology of seven southern neolithic sites in Karnataka and Andhra Pradesh. *Man Environ.* 26 (2), 47–66.

Korisettar, R., Venkatasubbaiah, P.C., Fuller, D.Q., 2001b. Brahmagiri and beyond: the archaeology of the southern neolithic. In: Settar, S., Korisettar, R. (Eds.), *Indian Archaeology in Retrospect, Volume 1 Prehistory, Archaeology of South Asia*. Manohar, New Delhi, pp. 151–237.

Lightfoot, E., Ustunkaya, M.C., Przelomska, N., O'Connell, T.C., Hunt, H.V., Jones, M.K., Petrie, C.A., 2019. Carbon and nitrogen isotopic variability in foxtail millet (*Setaria italica*) with watering regime. *Rapid Commun. Mass Spectrom.*: RCM. https://doi.org/10.1002/rcm.8615.

Lim, S.-S., Kwak, J.-H., Lee, K.-S., Chang, S.X., Yoon, K.-S., Kim, H.-Y., Choi, W.-J., 2015. Soil and plant nitrogen pools in paddy and upland ecosystems have contrasting δ 15 N. *Biol. Fertil. Soils* 51 (2), 231–239.

Misra, V.D., 1999. Agriculture, domestication of animals and ceramic and other industries in prehistoric India: mesolithic and Neolithic. Dawn Civ. Upto 600, 233–266.

Mohanty, R.K., Joglekar, P.P., Thakuria, T., Ray, S., Vaidya, S., Midhun, C.S., Wannapat, R., Sabnis, V., Bedekar, G., Pradhan, T., Yogesh Mallinathpur, M., 2012. PRELIMINARY REPORT ON EXPLORATION AT GOLBAI SASAN, TALAPADAAND THE SURROUNDING AREA, DIST. KHURDA, ODISHA, 2010-11, 72/73. *Bulletin of the Deccan College Research Institute*, pp. 153–166.

Mujumdar, G.G., Rajaguru, S.N., 1966. *Ashmound Excavations at Kupgal,* vol. 56. Deccan College Postgraduate & Research Institute.

Murphy, C., Fuller, D.Q., 2017. Seed coat thinning during horsegram (*Macrotyloma uniflorum*) domestication documented through synchrotron tomography of archaeological seeds. *Sci. Rep*. 7 (1), 5369.

Nadelhoffer, K.J., Fry, B., 1994. Nitrogen isotope studies in forest ecosystems. In: Lathja, K., Michener, R.H. (Eds.), *Stable Isotopes in Ecology and Environmental Science*. Blackwell Scientific, Oxford, pp. 22–44.

Nitsch, E., Andreou, S., Creuzieux, A., Gardeisen, A., Halstead, P., Isaakidou, V., Karathanou, A., Kotsachristou, D., Nikolaidou, D., Papanthimou, A., Others, 2017. A bottom-up view of food surplus: using stable carbon and nitrogen isotope analysis to investigate agricultural strategies and diet at Bronze Age Archontiko and Thessaloniki Toumba, northern Greece. *World Archaeol*. 49 (1), 105–137.

Nitsch, E.K., Charles, M., Bogaard, A., 2015. Calculating a statistically robust δ13C and δ15N offset for charred cereal and pulse seeds. *STAR: Sci. Technol. Archaeol. Res.* 1 (1), 1–8.

Paddayya, K., 1991. The ashmounds of South India: fresh evidence and possible implications. *Bull. Deccan College Res. Inst.* 51/52, 573–626.

Paddayya, K., 1993. Ashmound investigations at Budihal, Gulbarga district, Karnataka. *Man Environ*. 18 (1), 57–88.

Paddayya, K., 2000. The problem of ashmounds of southern deccan in the light of budihal excavations, Karnataka. *Bull. Deccan College Res. Inst.* 60/61, 189–225.

Peukert, S., Bol, R., Roberts, W., Macleod, C.J.A., Murray, P.J., Dixon, E.R., Brazier, R.E., 2012. Understanding spatial variability of soil properties: a key step in establishing field-to farm-scale agro-ecosystem experiments. *Rapid Commun. Mass Spectrom.: RCM* 26 (20), 2413–2421.

Prasad, S., Anoop, A., Riedel, N., Sarkar, S., Menzel, P., Basavaiah, N., Krishnan, R., Fuller, D., Plessen, B., Gaye, B., R¨ohl, U., Wilkes, H., Sachse, D., Sawant, R., Wiesner, M.G., Stebich, M., 2014. Prolonged monsoon droughts and links to Indo-Pacific warm pool: a Holocene record from Lonar Lake, central India. *Earth Planet Sci. Lett.* 391, 171–182.

Ruddiman, William F., 2003. The anthropogenic greenhouse era began thousands of years ago. *Clim. Change* 61, 261–293. https://doi.org/10.1023/B: CLIM.0000004577.17928.fa.

Renfrew, A.C., 1987. *Archaeology and Language: the Puzzle of Indo-European Origins*, first ed. Pimlico.

Renfrew, C., 2000. Archaeogenetics: towards a population prehistory of Europe. In: Renfrew, C., Boyle, K. (Eds.), *Archaeogenetics: DNA and the Population Prehistory of Europe*. McDonald Institute, pp. 3–12.

Roberts, P., Boivin, N., Petraglia, M., Masser, P., Meece, S., Weisskopf, A., Silva, F., Korisettar, R., Fuller, D.Q., 2016. Local diversity in settlement, demography and subsistence across the southern Indian Neolithic-Iron Age transition: site growth and abandonment at Sanganakallu-Kupgal. *Archaeol. Anthropol. Sci.* 8 (3), 575–599.

Sage, R.F., Monson, R.K., 1999. In: Sage, R.F., Monson, R.K. (Eds.), *C4 Plant Biology*. Elsevier.

Saraswat, K.S., 2005. Agricultural background of the early farming communities in the Middle Ganga Plain. *Pragdhara* 15, 145–177.

Santana-Sagredo, F., et al., 2021. 'White gold'guano fertilizer drove agricultural intensification in the Atacama Desert from AD 1000. *Nature Plants*.

Silvan, J.M., van de Lagemaat, J., Olano, A., Del Castillo, M.D., 2006. Analysis and biological properties of amino acid derivates formed by Maillard reaction in foods. *J. Pharmaceut. Biomed. Anal.* 41 (5), 1543–1551.

Styring, A.K., Ater, M., Hmimsa, Y., Fraser, R., 2016a. Disentangling the Effect of Farming Practice from Aridity on Crop Stable Isotope Values: A Present-Day Model from Morocco and its Application to Early Farming Sites in …. *The Anthropocene*. https://journals.sagepub.com/doi/abs/10.1177/2053019616630762.

Styring, A.K., Charles, M., Fantone, F., Hald, M.M., McMahon, A., Meadow, R.H., Nicholls, G.K., Patel, A.K., Pitre, M.C., Smith, A., Sołtysiak, A., Stein, G., Weber, J.A., Weiss, H., Bogaard, A., 2017. Isotope evidence for agricultural extensification reveals how the world's first cities were fed. *Nat. Plant* 3, 17076.

Styring, A.K., Manning, H., Fraser, R.A., Wallace, M., 2013. The effect of charring and burial on the biochemical composition of cereal grains: investigating the integrity of archaeological plant material. *J. Health.com*. https://www.sciencedirect.com/science/article/pii/S0305440313001192.

Styring, A., Maier, U., Stephan, E., Schlichtherle, H., 2016b. Cultivation of choice: new insights into farming practices at Neolithic lakeshore sites. *Antiquity*.

ACB0CAC3A8823A3C30F151D5E9827315.

Subbarao, B., 1948. *Stone Age Cultures of Bellary, Being a Report of the Excavation of Sanganakallu,* vol. 7. Deccan College Postgraduate and Research Institute.

Sundara, A., 1987. Studies in ash mounds. In: Pande, B.M., Chattopadhyaya, B.D. (Eds.), *Archaeology and History: Essays in Memory of Shri A. Ghosh*, vol. I. Agam Kala Prakashan, Delhi, pp. 313–324.

Szpak, P., 2014. Complexities of nitrogen isotope biogeochemistry in plant-soil systems: implications for the study of ancient agricultural and animal management practices). *Front. Plant Sci.* https://doi.org/10.3389/fpls.2014.00288.

Tashi, Sonam, Singh, Balwant, Keitel, Claudia, Adams, Mark, 2016. Soil carbon and nitrogen stocks in forests along an altitudinal gradient in the eastern Himalayas and a meta-analysis of global data. *Global Change Biol*. https://doi.org/10.1111/gcb.13234.

Treasure, E.R., Church, M.J., Gr¨ocke, D.R., 2016. The influence of manuring on stable isotopes (δ13C and δ15N) in Celtic bean (Vicia faba L.): archaeobotanical and palaeodietary implications. *Archaeol. Anthropol. Sci.* 8 (3), 555–562.

Vaiglova, P., Snoeck, C., Nitsch, E., Bogaard, A., Lee-Thorp, J.A., 2014. Investigating the most appropriate laboratory pre-treatment method on archaeological charred grain/ seed remains for stable isotope analysis (δ13C and δ15N). *Rapid Commun. Mass Spectrom.: RCM* 28, 2497–2510.

Wallace, M., Jones, G., Charles, M., Fraser, R., Halstead, P., Heaton, T.H.E., Bogaard, A., 2013. Stable carbon isotope analysis as a direct means of inferring crop water status and water management practices. World Archaeol. 45 (3), 388–409.

Wallace, M.P., Jones, G., Charles, M., Fraser, R., Heaton, T.H.E., Bogaard, A., 2015. Stable carbon isotope evidence for neolithic and bronze age crop water management in the eastern Mediterranean and southwest Asia. *PLoS One* 10 (6), e0127085.

Yousfi, S., Serret, M.D., Araus, J.L., 2009. Shoot δ15N gives a better indication than ion concentration or Δ 13C of genotypic differences in the response of durum wheat to salinity. *FUnct. Plant Biol.* 36, 144