Direct evidence for agricultural intensification during the first two millennia AD in northeast Burkina Faso

Amy K. Styring[1*], Alexa Höhn[1], Veerle Linseele[2], Katharina Neumann[1]

[1] Abteilung III: Vor- und Frühgeschichte, Institut für Archäologische Wissenschaften, Sprach- und Kulturwissenschaften Fachbereich 09, Goethe-Universität Frankfurt, Frankfurt am Main, Germany.

[2] Laboratory of Biodiversity and Evolutionary Genomics, KU Leuven, Belgium

* Corresponding author

Email: styring@em.uni-frankfurt.de

Abstract

Archaeobotanical evidence from archaeological sites in northeast Burkina Faso dating to the first and second millennia AD has provided a useful insight into crop cultivation and the development of the West African savanna landscape. Nitrogen isotopic analysis of charred pearl millet grains from the same sites now provides the first opportunity to investigate how increased crop production and permanence of cultivated fields related to the intensity of household waste/manure application. Nitrogen isotope values of pearl millet grains increased during the first two millennia AD, indicating an intensification of manuring that would have enabled soil to stay fertile for longer, reducing the agricultural footprint of shifting cultivation. This may have been advantageous as population and settlement density increased, thereby increasing competition over land. The intensity of manure application in the second millennium AD at sites close to the Mare d'Oursi suggests that manure was likely sourced from outside the farming settlements, from livestock herded by nomadic pastoralists who would have been drawn to the *mare* for water. This is rare evidence for specialisation of sedentary farmers and pastoralists, demonstrating how the novel combination of fruit/seed, charcoal, faunal and isotopic evidence used in this study can enrich our knowledge of past lifeways in West Africa.

Keywords

West Africa; pearl millet; nitrogen isotopes; manuring; $\delta^{15}N$; pastoralism

1. Introduction

1.1 The first two millennia AD in West Africa

The first two millennia AD (cal AD 0–1400) were a time of significant social, technological and economic change in West Africa. Large settlement mounds appeared, formed from the accumulation of cultural and organic materials, which attest to the beginning of long-term sedentary occupation (Albert et al., 2004: 123–128; McIntosh, 1994). Plant and faunal remains point to farming having been well-established from the beginning of the mound sequence, with subsistence based on crop cultivation and livestock husbandry, supplemented by the gathering of wild plants, fishing and hunting (Kahlheber and Neumann, 2007). While iron metallurgy had been well-established in Africa from the middle of the first millennium BC (Chirikure, 2013), iron artefacts remained rare until larger scale production began in the second millennium cal AD (Barros, 1986; Serneels, 2017). There is evidence for trade in exotic goods from the second half of the first millennium AD (Magnavita, 2013), which may have supported the rise of urban centres and the emergence of the first West African kingdoms of Ghana, Gao, Mali and Songhai (MacDonald, 2013: 838–840). These empires controlled regional economies exchanging commodities such as grain, animal products, gold and iron across the Sahara. In the 14th century AD, there was widespread depopulation of settlement mounds in northern Burkina Faso, northern Cameroon and in the Méma region of Mali (McIntosh, 1994; Togola, 1996; Vogelsang et al., 1999). This abandonment of sedentary sites has been attributed to climate, disease and/or [resulting] political instability, which led to a shift to more mobile lifestyles (McIntosh, 1998: 242).

A key question is: How did the agricultural economy change and underpin these economic and societal changes in West Africa during the first two millennia AD? Archaeobotanical information for this period is available from Senegal (Gallagher, 1999; Gallagher et al., 2018; Murray, 2008; Murray et al., 2007), Mali (Gestrich and MacDonald, 2018), Burkina Faso (Kahlheber, 2004), Nigeria (Bigga and Kahlheber, 2011; Klee et al., 2000), Cameroon (Otto and Delneuf, 1998) and Benin (Champion and Fuller, 2018). The Malian urban centres of Dia (Murray, 2005), Jenne-Jeno (McIntosh, 1995: 348–351), Gao (Fuller, 2000), and Essouk-Tadmakka (Nixon et al., 2011) have also been investigated archaeobotanically. These investigations have generally revealed cultivation of pearl millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*) and African rice (*Oryza glaberrima*) in varying proportions. In many of these cases, however, material is relatively scarce and therefore little more than the presence or absence of different plants can be reasonably compared (Neumann, 2018).

1.2 Subsistence in northeast Burkina Faso

Archaeobotanical assemblages from settlement mounds in northeast Burkina Faso have provided some of the richest information on subsistence in the first two millennia in West Africa to date. The settlement mounds were situated close to *mares* and rivers, providing [semi-]permanent water sources for people and livestock, and sandy soils, which are easy to cultivate (Albert et al., 2004: 225). Systematic investigation of plant remains from settlement sites (Fig 1) dated to between cal AD 0 and 1400 has provided evidence for the cultivation of domesticated pearl millet, probably intercropped with cowpea (*Vigna unguiculata*). This would have served to increase yields on the same area of land and maintain soil fertility, whilst also improving resilience in the event of one crop failing (Kahlheber and Neumann, 2007).

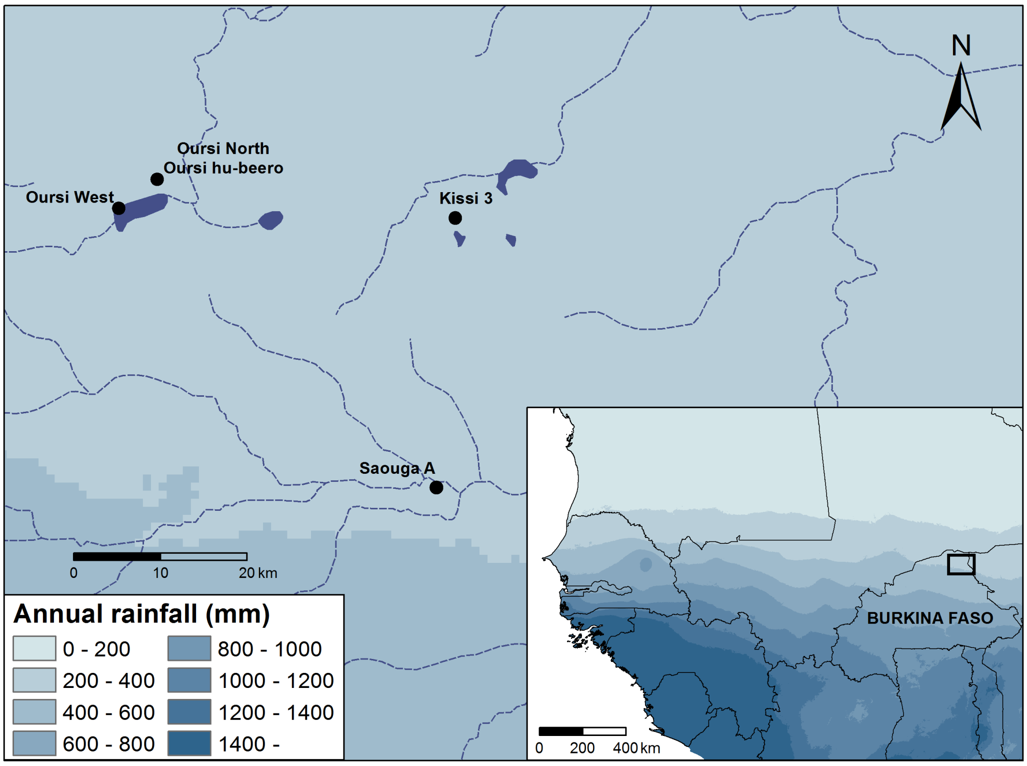

Fig 1. Map showing location of archaeological sites in northeast Burkina Faso. Shading denotes annual rainfall derived from interpolation of average monthly climate data for 1970–2000, available from the WorldClim database, version 2 (Fick and Hijmans, 2017).

There was little change in the spectrum of plant remains during the first two millennia AD. Bambara groundnut (*V. subterranea*) and roselle (*Hibiscus sabdariffa*) supplemented pearl millet and cowpea in low numbers throughout the period. Sorghum appeared in low numbers at the site of Oursi North from around cal AD 700–800, but the lack of threshing waste (in comparison to the large amounts for pearl millet) suggests that it could have been imported into the site as part of the trans-Saharan trade network (Kahlheber, 2004: 225). An increase in the size (width, length and breadth) of pearl millet grains (between cal AD 100 and 1100) may reflect an improvement in growing conditions and soil fertility through time (Kahlheber, 2004: 222).

Charcoal analysis at the same sites in Burkina Faso has shown a decrease in the presence of *Acacia* sp. during this period (Höhn and Neumann, 2012). These trees are characteristic of the natural savanna vegetation (Le Houérou, 1989) and their dominance in the first half of the first millennium AD suggests that when pearl millet and cowpea cultivation first became an important part of the subsistence strategy, cultivated fields had little impact on the natural vegetation. This has been attributed to the practice of shifting cultivation, whereby fields are cultivated for one or two years, before being left fallow for at least 20 years so that the natural vegetation can re-grow and soil nutrients can be replenished (Höhn and Neumann, 2012).

During the course of the first two millennia AD, the natural *Acacia* savanna vegetation was replaced by Combretaceae species, which are characteristic of areas that have been cultivated and then left fallow or uncultivated for a number of years. In the first millennium AD, *Anogeissus leiocarpus* was the predominant Combretaceae species, pointing to relatively long fallow periods because it regenerates slowly in relation to other species in the Combretaceae family (Donfack et al., 1995). By AD 1000, these long-term fallows (c. 5–22 years) were interspersed with shorter-term fallows, dominated by *Guiera senegalensis*, *Combretum micranthum* and *Combretum glutinosum*, which recover more quickly after clearance. Certain trees, such as the shea tree (*Vitellaria paradoxa*), marula (*Sclerocarya birrea*), baobab (*Adansonia digitata*), tamarind (*Tamarindus indica*) and *Faidherbia albida* are protected within cultivated fields due to the useful properties of their fruits, seeds and/or leaves (Pullan, 1974). Seeds and charcoal from these trees are also present in the archaeobotanical assemblages from northeast Burkina Faso, pointing to their presence within the fields. By the second millennium, then, the landscape was characterised by a mosaic of fields and fallows, dotted with useful trees, much like the parkland savanna that is found in Burkina Faso today (Hahn-Hadjali, 1998).

G. senegalensis is characteristic of young fallows but also recovers well after grazing and its seeds are distributed by livestock, making it a good indicator of the intensity of grazing (Arbonnier, 2009: 267). Together with *F. albida* it is an important source of fodder for cattle in particular; leaves and branches (and the fruit of *F. albida*) are collected in the dry season when grass is less readily available (Toutain, 1980). At Oursi hu'beero, dated to around cal AD 1100 (Petit and Czerniewicz, 2011), a room identified as a stall due to the presence of preserved sheep dung pellets contained fragments of *G. senegalensis* charcoal, highlighting its role in the livestock diet (Höhn, 2005: 99, 105). The increase in *G. senegalensis* and *F. albida* in the charcoal assemblages (Höhn, 2005: 116), as well as the increased importance of domestic livestock (namely sheep and goats) in the archaeozoological assemblages (Linseele, 2007: 157), points to an intensification in the herding of livestock in the second compared to the early first millennium AD.

The increasing frequency of cultivation would have removed more nutrients from the soil, reducing its fertility and therefore potentially reducing crop yields. It has been speculated that soil nutrients were replaced by addition of cattle manure, likely through grazing of the fields in the dry season, following the harvest (Höhn and Neumann, 2012), as occurs today and as occurred in the recent past (Krings 1991; Le Houérou, 1989; Prudencio 1993; Styring et al., 2019). Cultivated fields close to homesteads (within c. 500 m) today also receive inputs of household waste (including animal manure and ash), which is generally spread by hand (Adderley et al., 2004; Pelissier 1966; Prudencio 1993). Until now, the theory that manuring permitted the increasing frequency of cultivation during the second millennium AD has not been explicitly tested. New methods now make it possible to identify manuring practices directly, by determining the nitrogen isotope values of ancient charred (carbonised) plant remains.

1.3 Determining manuring intensity through isotopic analysis of crop remains

Addition of manure to soil has been found to increase the nitrogen isotope ($\delta^{15}N$) values of cereal grains, according to the amount and frequency of its application (Fraser et al., 2011).

Moreover, it has been shown that charred cereal grains recovered from archaeological sites retain their original $\delta^{15}N$ values (DeNiro and Hastorf, 1985; Fraser et al., 2013). As a result, nitrogen isotope analysis of archaeobotanical remains has been used to reconstruct the intensity of manuring of arable fields and determine how this varied spatially and temporally at a number of archaeological sites in Europe and southwest Asia (e.g. Bogaard et al., 2013; Gron et al., 2017; Nitsch et al., 2017; Styring, Rösch, et al., 2017; Styring, Charles, et al., 2017; Vaiglova, Bogaard, et al., 2014; Vignola et al., 2017).

Plant $\delta^{15}N$ values can vary due to many other factors, however, including differences in mycorrhizal associations (Craine et al., 2009), soil texture (Aranibar et al., 2004), depth from which plants obtain their N (Hobbie and Ouimette, 2009), temperature (Amundson et al., 2003) and rainfall (Craine et al., 2009). This means that it is not possible to directly equate a cereal grain $\delta^{15}N$ value with a specific manuring level, without taking into account regional climate, in particular. The $\delta^{15}N$ values of > 11,000 plants collected globally were observed to negatively correlate with annual rainfall, independently from the effect of manuring (Craine et al., 2009). A linear model was therefore developed to allow the manuring level of an archaeological cereal grain sample to be predicted based on its $\delta^{15}N$ value and the estimated annual rainfall of its growing location (Styring, Charles, et al., 2017).

While the linear model was primarily based on the $\delta^{15}N$ values of wheat and barley grains sampled from fields in Eurasia, a recent study found that the $\delta^{15}N$ values of modern pearl millet grains growing in plots receiving modest levels of manure/household waste in three regions in Senegal (mean annual rainfall between 494 and 565 mm) fit well into the low and medium manuring levels defined by the model (Styring et al., 2019). Since then, Reid et al. (2018) found that the $\delta^{15}N$ values of pearl millet grown in four different years at the Germplasm Introduction and Research Unit, Kingshill, United States Virgin Islands, with annual rainfall ranging from 807–1353 mm, correlated *positively* with annual rainfall (an opposite relationship to that observed globally among all plant types). If the positive relationship between pearl millet $\delta^{15}N$ values and rainfall is found to be valid at a wider range of annual rainfall values, use of the current linear model to infer manuring level from pearl millet $\delta^{15}N$ values and rainfall will thus need to be modified. Reid et al. (2018) also found a positive correlation between pearl millet carbon isotope ($\delta^{13}C$) values and annual rainfall, but a negative correlation with mean growing season temperature. This makes it difficult to investigate climatic change using pearl millet $\delta^{13}C$ values, since a decrease in rainfall may well be accompanied by an increase in temperature, thus cancelling out any directional effect of aridity on the carbon isotopic composition. Until further studies are carried out to more conclusively assess the relationship between pearl millet $\delta^{15}N$ and $\delta^{13}C$ values and annual rainfall and temperature, we must rely on external proxies to infer whether archaeological pearl millet $\delta^{15}N$ values are likely to have been affected by changes in climate.

This study takes a broad look at how pearl millet grain $\delta^{15}N$ values changed during the first two millennia AD, from AD 100–1400, at five sites in northeast Burkina Faso (Fig 1). Details of these sites are given in Table 1. Combined with the systematic and detailed investigations of subsistence and vegetation change at these sites, nitrogen isotope values of 98 pearl millet grain samples provide a long-term view of how people managed their land and ensured sufficient crop yields in response to increased demands for food. Animal bones from the same stratigraphic units were also sampled with a view to determine their carbon and nitrogen isotopic compositions, which could be compared with the pearl millet grain $\delta^{15}N$ values. The $\delta^{13}C$ values of the pearl millet samples were also determined to assess whether they co-vary with the $\delta^{15}N$ values.

Table 1. Description of the settlement mounds in northeast Burkina Faso where pearl millet grains were sampled for nitrogen and carbon isotope analysis.

Site	Location (latitude °N, longitude °E)	Approximate dates	Description	Context	Sampling
Oursi West	14.66, -0.50	AD 100–300	Settlement mound with preceding layers dating to the first millennium BC	Highest mound in a group of 12 closely grouped mounds located close to the permanent Mare d'Oursi lake	Arbitrary 10 cm deep units excavated from three square metre quadrats

Kissi 3 and 3B	14.65, -0.15	AD 670–880	Burial site with evidence for exotic goods (Kissi 3) adjacent to a settlement mound (Kissi 3B)	Part of a group of settlement mounds, necropoles and stone circles. On the northern shore of the Mare de Kissi lake, which is seasonally wet	Samples taken from each archaeological context. Plant remains recovered from burial site but interpreted as coming from settlement mound
Oursi Nord	14.69, -0.46	AD 400–1250	Settlement mound	Highest mound in a group of 25 mounds (average diameter 100-200 m), which cover c. 80 ha about 2 km from the permanent Mare d'Oursi lake	Arbitrary 10 cm deep units excavated from two square metre quadrats
Saouga A	14.37, -0.17	AD 1000–1200	Settlement mound	Part of a group of 14 settlement mounds, 20 m in diameter, 1-2 km from the seasonally wet Gorouol river	Arbitrary 10 cm deep units excavated from three square metre quadrats
Oursi hu-beero	14.69, -0.46	AD 1100	Remains of mud-brick buildings on a settlement mound	A homestead (450 m^2) that was burned to the ground and borders Oursi North to its east	Samples taken from each archaeological context, some hand-picked and some by flotation

2. Materials and methods

2.1 Sampling of archaeobotanical remains

Each archaeological site (with the exception of Oursi hu-beero) was excavated in 10 cm deep units, with an archaeobotanical sample taken from each unit in each quadrat, by a team of archaeologists at the Goethe Universität-Frankfurt (details in Kahlheber, 2004). At Oursi hu-beero, each archaeological feature was treated as a distinct context and plant remains were either hand-picked or recovered by flotation (Petit and Czerniewicz, 2011). Pearl millet grains recovered by flotation from the archaeological sites of Oursi West (BF94/45), Kissi 3 (BF96/3), Oursi North (BF97/13), Saouga A (BF94/120) and Oursi hu-beero (BF97/30) were identified by S. Kahlheber as part of her doctoral thesis (Kahlheber, 2004). Kahlheber investigated the contents of archaeobotanical samples taken approximately every 30–50 cm in depth. Additional samples of pearl millet grains were selected from intermediate units and identified by A. Styring and B. Eichhorn as part of this study. Between 9 and 15 grains (weighing 5–55 mg) were selected from each archaeobotanical sample for isotopic analysis. Each sample thus comprises 9–15 grains from each context. Details of the archaeological contexts of the samples are given in Supplementary material (Table S1). Two samples, from Kissi 3 and Oursi hu-beero, were scraped clean, crushed and analysed using Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR) to look for the presence of carbonate, nitrate and/or humic contamination (after Vaiglova, Snoeck, et al., 2014). No evidence for contamination was observed (Supplementary material, Fig S1) and so the remaining samples were scraped clean using a scalpel before being crushed using an agate mortar and pestle.

2.2 Extraction of bone collagen from animal bones

Animal bones were recovered from the same stratigraphic units as archaeobotanical samples. These were identified by V. Linseele as part of her PhD thesis (Linseele, 2007). A sub-sample of 60 bones identified as large bovids (likely cattle), cattle (*Bos primigenius* f. taurus), sheep (*Ovis* aries), goat (*Capra aegagrus* f. hircus), sheep/goat or wild herbivores – including antelopes, bohor reedbuck (*Redunca redunca*), bush duiker (*Sylvicapra grimmia*), kob (*Kobus kob*), oribi (*Ourebia ourebi*) and red-fronted gazelle (*Gazella rufifrons*) – were selected from Oursi West, Oursi North, Saouga A and Oursi hu-beero to test for collagen preservation. Between 0.5 and 1 g of bone was cleaned of any visible dirt or carbonate crusts using a drill bit before being roughly crushed. Bone pieces were then soaked in 0.5 M hydrochloric acid; the acid was changed every second day. After approximately two weeks, the acid was decanted and the bone residue rinsed three times with distilled water. Acidified distilled water (pH 3) was then added and the mix heated at 75°C for 48 h. The liquid was separated from any residue using an Ezee Filter, 60–90 µm (OEA Laboratories Limited, UK), and then freeze-dried. Fifteen of these samples with the cleanest and fluffiest-looking 'collagen-isolate' were selected for isotopic analysis.

2.3 Laboratory analysis

The homogenised powders of the archaeological pearl millet grains and bone collagen isolates were weighed into tin capsules for isotopic analysis on a Thermo MAT 253 continuous flow isotope ratio mass spectrometer coupled to a Thermo Flash 1112 Series elemental analyser in the Institut für Geowissenschaften, Goethe-Universität Frankfurt, Germany. Isotopic data are provided in Supplementary material (Table S2). The nitrogen contents of the samples were calculated based on the area under the N_2 peak relative to the weight of the sample, calibrated using IAEA-N2. Following the method presented by Szpak et al. (2017), measurement uncertainty in %N content was monitored using two in-house standards (DL-leucine, %N 10.7%, DL-glutamic acid monohydrate, %N = 8.5%). Precision ($u(R_w)$) was determined to be ± 0.3% on the basis of repeated measurements of calibration standards, check standards and sample replicates. Accuracy or systematic error ($u(bias)$) was determined to be ± 0.5% on the basis of the difference between the observed and known %N contents of the check standards. Using the equation presented in Supplementary material (Table S3), the total analytical uncertainty in %N content was estimated to be ± 0.6%. The carbon contents of the samples were calculated based on the area under the CO_2 peak relative to the weight of the sample, calibrated using IAEA-C7. Measurement uncertainty in %C content was monitored using two in-house standards (DL-leucine, %C 54.9%, DL-glutamic acid monohydrate, %C = 36.4%). $u(R_w)$ was determined to be ± 2.2% on the basis of repeated measurements of calibration standards, check standards and sample replicates, *u*(*bias*) was determined to be ± 1.0% on the basis of the difference between the observed and known %C contents of the check standards. The total analytical uncertainty in %C content was estimated to be ± 2.4% (Table S3). Stable nitrogen isotope values were calibrated to the AIR scale using IAEA-N1 (δ^{15}N 0.4 ± 0.2 ‰) and IAEA-N2 (δ^{15}N 20.3 ± 0.2 ‰). Measurement uncertainty in δ^{15}N values was monitored using three in-house standards: LEU (DL-leucine, δ^{15}N 6.46 ± 0.40 ‰), GLU (DL-glutamic acid monohydrate, δ^{15}N –1.87 ± 0.07 ‰) and MIL (millet flour from a single panicle from a plot in Senegal, δ^{15}N 3.14 ± 0.63 ‰). Precision ($u(R_w)$) was determined to be ± 0.18 ‰, accuracy or systematic error (*u*(*bias*)) was ± 0.59 ‰ and the total analytical uncertainty in δ^{15}N values was estimated to be ± 0.61 ‰ using the equation presented in Supplementary material (Table S3). Stable carbon isotope values were calibrated to the VPDB scale using IAEA-C7 (δ^{13}C –32.15 ± 0.05 ‰) and IAEA-USGS24 (δ^{13}C –16.05 ± 0.04 ‰). Measurement uncertainty in δ^{13}C values was monitored using three in-house standards: LEU (DL-leucine, δ^{13}C –28.26 ± 0.07 ‰), GLU (DL-glutamic acid monohydrate, δ^{13}C –10.41 ± 0.09 ‰) and MIL (millet flour from a single panicle from a plot in Senegal, δ^{13}C –10.21 ± 0.09 ‰). $u(R_w)$ was determined to be ± 0.06 ‰, *u*(*bias*) was ± 0.11 ‰ and the total analytical uncertainty in δ^{13}C values was estimated to be ± 0.13 ‰ (Table S3). Statistical analyses were performed in R (3.4.3).

2.4 Chronology

Charcoal from various stratigraphic levels was radiocarbon dated at all sites (see Höhn, 2005 for dates). To provide a rough chronology of samples within each site’s stratigraphy, a constant sediment accumulation rate was assumed. The most recent date in the calibrated date range from the highest dated stratigraphic level was treated as the *terminus ante quem* and the oldest date in the calibrated date range of the lowest dated stratigraphic level treated as the *terminus post quem*. The depth of the sample within this range was then used to calculate its approximate date. At Oursi North, the material between 550 and 810 cm below the surface dated to between cal AD 426 and 885 (c. 400 years in 260 cm), whereas the material between 50 and 550 cm below the surface dated to between cal AD 885 and 1250 (c. 400 years in 500 cm). The difference in sedimentation rate between these two zones means that they were treated separately when estimating dates. All samples from Oursi hu’beero were assumed to be contemporaneous and to date to around cal AD 1100, when a sizeable homestead was present at the site (Petit and Czerniewicz, 2011). The single sample from Kissi 3 was assigned a date of cal AD 800 because it derived from a settlement mound (Kissi 3B) that was radiocarbon dated to between cal AD 670 and 880 (Magnavita, 2006: 38). Estimated dates for each sample are given in Supplementary material (Table S1).

3. Results

The %N and %C content and δ^{15}N and δ^{13}C values of each pearl millet grain sample included in this study are given in Supplementary material (Table S2). Prior to graphing and analysis, these δ^{15}N and δ^{13}C values were corrected for charring by subtracting 0.34 ‰ and 0.11 ‰, respectively, from the determined δ^{15}N and δ^{13}C values (after Styring et al., 2019). Only the first analysed of the duplicate samples (i.e. those without an "a" following the SampleID) are included in the following analyses. The pearl millet %N contents range from 1.6 to 5.2% (Fig 2). The majority of archaeological pearl millet %N contents fall within the range of the %N contents of modern pearl millet grains heated for between 2 and 24 h at 215°C to 260°C (shaded region in Fig 2; values are taken from Styring et al., 2019). One of the samples has a higher %N content and others have slightly lower %N contents than the modern charred millet grains. However, the range of %N contents of modern samples is derived from only one study by Styring et al. (2019), which considered modern commercial cultivars, and it is likely that ancient pearl millet had a more diverse range of %N contents. Furthermore, the δ^{15}N values of these samples do not appear anomalous and therefore we have included these in further analysis and interpretation.

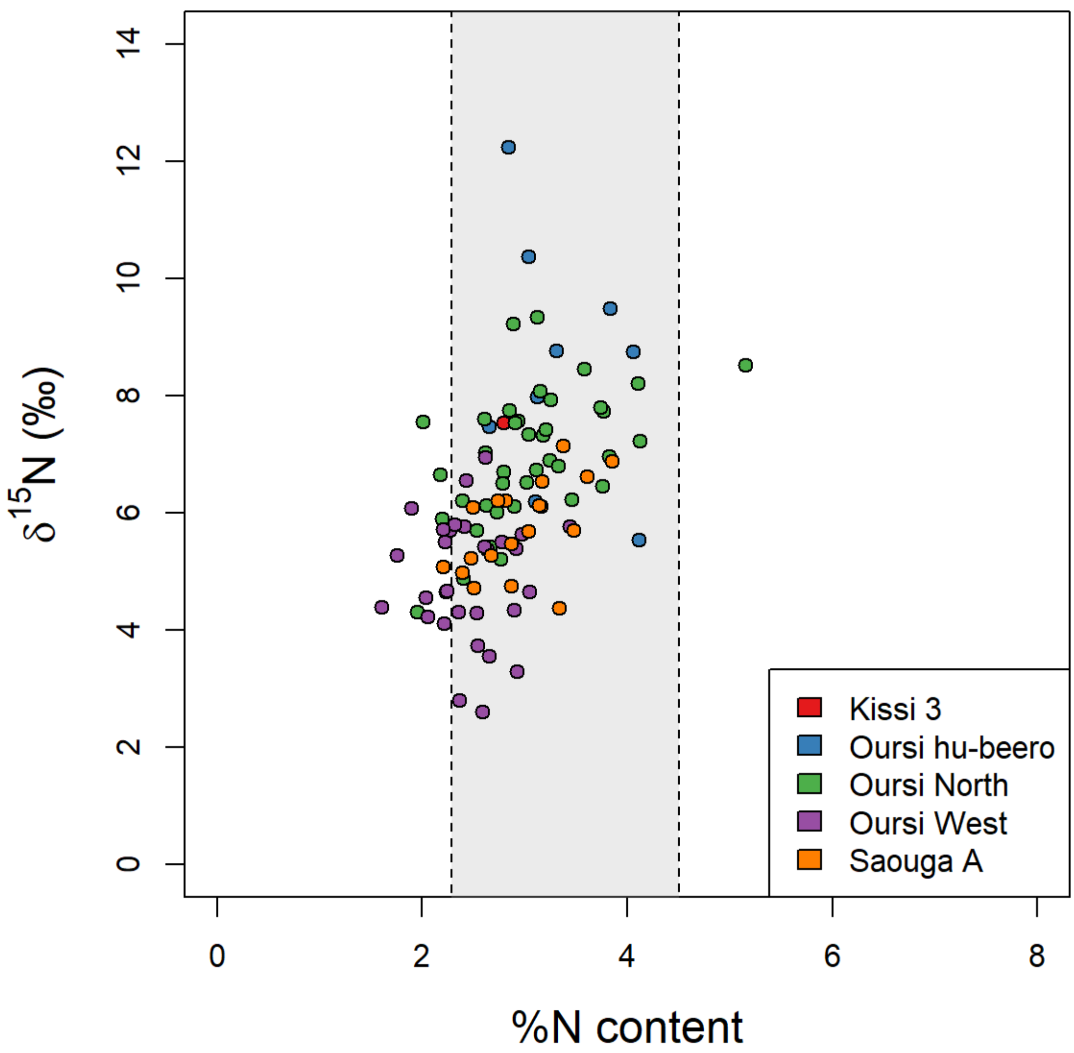

Fig 2. Plot of archaeological charred pearl millet δ^{15}N values against their %N content. Samples are colour-coded by site. Shading shows the range in %N contents of modern pearl millet grain samples from Senegal, charred by heating to 215–260°C for 2–24 hours (data from Styring et al., 2019).

The pearl millet δ^{15}N values range from 2.9 to 12.6 ‰ and are normally distributed, both overall ($W = .978$, $p = .108$) and within sites. A linear mixed-effects model between pearl millet δ^{15}N values and date, including a random effect of archaeological site, finds an increase in δ^{15}N values of 0.19 ‰ per century (Beta = .00189, SE = .000671, $t = 2.82$, $p = .006$) (Fig 3). A similar increase in δ^{15}N values of 0.16 ‰ per century is observed when only pearl millet grains from Oursi North, spanning a date range from c. cal AD 400 to 1250, are considered (Beta = .00155, SE = .000775, t = 2.00, p = .053).

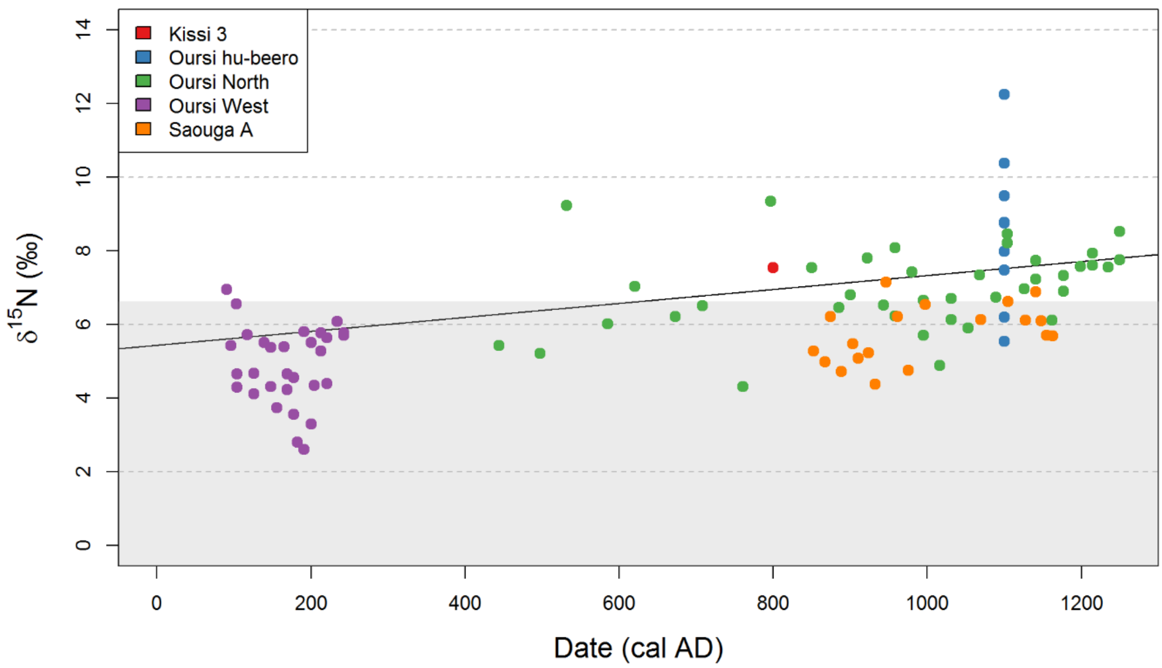

Fig 3. Plot of archaeological charred pearl millet δ^{15}N values against their date, estimated from stratigraphic position and radiocarbon dates. Samples are colour-coded by site. Shading shows the range in δ^{15}N values of modern uncharred pearl millet grain samples from Senegal, grown under low-medium manuring levels (Styring et al., 2019). The regression line shows the fixed effect of date on pearl millet δ^{15}N values (y = .00189x + 5.44).

The pearl millet δ^{13}C values range from –9.7 to –7.7 ‰ and are normally distributed, both overall (W = .994, p = .953) and within sites. Fig 4 plots pearl millet δ^{15}N values against their δ^{13}C values. A Pearson product-moment correlation coefficient was computed to assess the relationship between pearl millet δ^{15}N and δ^{13}C values and found that there was no correlation between the two variables (r = .125, n = 96, p = .218). A linear mixed-effects model, including a random effect of archaeological site, finds no relationship between pearl millet δ^{13}C values and date (Beta = .000099, SE = .000153, t = 0.65, p = .518) (Supplementary material, Fig S2). Moreover, no change is observed when only pearl millet grains from Oursi North, are considered (Beta = -.000009, SE = .000221, t = -0.0387, p = .969). Nevertheless, an analysis of variance (ANOVA) on the pearl millet sample δ^{13}C values yielded significant variation among sites (F(4, 93) = 12.9, p < .001). A post hoc Tukey test showed that the δ^{13}C values of pearl millet from Oursi West are significantly lower than those at the other sites, at p < .0446. The δ^{13}C values are not discussed further at it is currently unclear how these can be interpreted in terms of water availability and temperature.

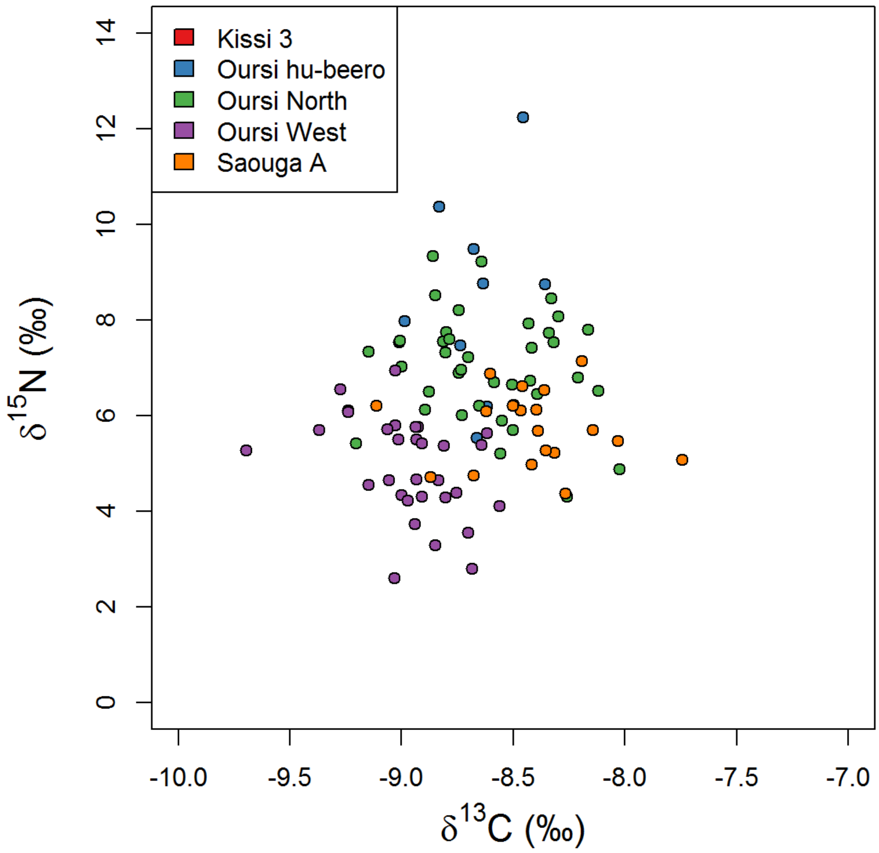

Fig 4. Plot of archaeological charred pearl millet δ^{15}N values against their δ^{13}C values, colour-coded by site.

The residue that was isolated from the bone samples comprised between 0.2 and 9.0% of the original bone mass (mean = 3.6%) (Supplementary material, Table S4). However, the residues selected for isotopic analysis only contained between 0.5 and 1.9% carbon and 0.2 and 0.6% nitrogen, whereas collagen should contain at least 30% carbon and 10% nitrogen (van Klinken, 1999). It is therefore clear that the residues from the collagen extraction protocol are not organic but likely to be exogenous contamination or highly degraded bone. No isotope values were therefore determined and no further bones were analysed from these sites.

Similarly poor collagen preservation was also found at other arid sites in the Mauritanian *Dhar* and Inner Niger Delta (Maurer et al., 2014).

4. Discussion

The increase in pearl millet $\delta^{15}N$ values during the first two millennia AD (Fig 3) points to an increase in manure/organic matter addition to arable fields. Such a consistent ^{15}N-enrichment could arguably alternatively be due to a unidirectional change in rainfall: a decrease in rainfall according to the negative correlation observed globally between plant $\delta^{15}N$ values and precipitation (e.g. Craine et al., 2009), or an increase in rainfall according to the positive correlation observed between pearl millet $\delta^{15}N$ values and precipitation by Reid et al. (2018). Reconstruction of the hydrological conditions during occupation of the archaeological sites, based on fluvial sediments of the Yamé River in Mali, around 350 km to their west, indicates similar conditions to those of the present-day, interspersed with periods when it may have been a little wetter (Lespez et al., 2011). The recovery of *V. paradoxa* charcoal from the archaeological sites in Burkina Faso, however, suggests that the climate was consistently wetter than the present-day throughout their occupation as *V. paradoxa* requires at least 600 mm annual rainfall (Hall et al., 1996). Since the Yamé River proxy evidence for past rainfall is more than 300 km away from the archaeological sites in this study, there is clearly a need for more investigations into the climatic conditions in this region during the settlement mound occupation. To date, however, these available proxies provide no indications that the climate became significantly drier or wetter during the occupation of the sites, suggesting that the increase in pearl millet $\delta^{15}N$ values is consistent with an intensification of manuring practices rather than progressive climatic change.

The increase of manure/organic matter input inferred from the pearl millet $\delta^{15}N$ values coincides with the increasing importance of cereal cultivation (Kahlheber, 2004: 238), increasing settlement density (Vogelsang et al., 1999) and reduction in the length of fallow periods, as evidenced by an increase in the proportion of charcoal from woody species that recover quickly after vegetation clearance (Höhn and Neumann, 2012; Neumann et al., 1998). This is the first direct evidence pointing to the fact that addition of household waste and/or animal manure enabled people to reduce the length of time that fields were left fallow, thus intensifying their agricultural production. Leaving fields fallow so that humus can re-accumulate after the removal of plant residues and thus nutrients during harvest is the lowest-cost method for regenerating soil fertility (Gallagher, 2010: 91). However, this becomes unfeasible when pressure for land increases, likely due to increasing population and settlement density, and it is no longer possible to clear larger areas for agriculture without having to compete over land with neighbours. Thus, the greater availability of manure may have been the driver for the longer-term cultivation of plots, allowing surplus production without continually shifting cultivation to new areas.

Interestingly, increasing manuring intensity to reduce the 'footprint' of land required for cultivation in Burkina Faso is the opposite of what occurred in northern Mesopotamia from c. 6500 BC to 2000 cal BC, as populations increased and urban centres began to emerge (Styring, Charles, et al., 2017). In this region, which today is northern Syria, manuring intensity of wheat and barley decreased as the size of population centres (used as a proxy for population) increased. This indicates that increased demand for cereals to feed growing populations was met by cultivating *larger* areas of land with lower manure inputs rather than investing more manure, and thus labour, to increase crop yields on the same area. A corollary of tying arable production to the area of land under cultivation is a greater importance of land-based wealth, which can be transferred from generation to generation (Borgerhoff Mulder et al., 2009). This can lead to inherited wealth inequality, which is clearly visible in the early urban centres of northern Mesopotamia (e.g. Oates et al., 2007). By contrast, in Burkina Faso, production seems to have been more dependent on access to manure or organic waste and the labour required to apply this to arable plots, and it appears that competition over land was minimised through higher manure and labour inputs. The increase in pearl millet $\delta^{15}N$ values during the first two millennia AD in northeast Burkina Faso is also in contrast to the situation from cal AD 500–1150 at Tongo Maaré Diabal, Mali, where the $\delta^{15}N$ values of pearl millet samples remained relatively constant throughout the occupation of the site (Styring et al., 2019), in conjunction with little change in vegetation (Gestrich and MacDonald, 2018). Perhaps here, the focus was less on agricultural surplus and more on iron production, given the evidence for intensive iron-working on the site and its surrounding settlements (Gestrich and MacDonald, 2018). Therefore the intensity of agriculture may not have changed as much during the site's occupation as it did in northeast Burkina Faso.

It is likely that the increase in pearl millet $\delta^{15}N$ values from Burkina Faso is due to an increase in the application of *animal* manure. Studies of present-day small-scale societies in China have found that households produce relatively little household waste (0.25 t human waste per person plus 0.15 t of household waste per year (FAO, 1978: 27)). Manure from livestock – particularly from cattle – therefore plays a key role in supplementing this (c. 6 t per year per cow, 3 t per year per pig, 0.8 t per year per sheep/goat (FAO, 1978: 27)). Moreover, the increase in pearl millet $\delta^{15}N$ values in northeast Burkina Faso is concomitant with an increase in charcoal from *G. senegalensis* and *F. albida*, both of which are associated with livestock grazing; *G. senegalensis* is considered an indicator of overgrazing (Arbonnier, 2009: 267) and *F. albida* is a favoured source of fodder for cattle (Toutain, 1980).

At Saouga A, pearl millet $\delta^{15}N$ values are lower than contemporaneous pearl millet samples from Oursi North (Fig 3) ($t(41.2) = 5.64$, $p < .001$, mean $\delta^{15}N$ value of samples from Oursi North dated to later than AD 800 = 7.4 ‰, mean $\delta^{15}N$ value of samples from Saouga A = 6.1 ‰). At Saouga A, quantities of *G. senegalensis* and *F. albida* are also significantly lower than at Oursi North (Höhn and Neumann, 2012; Neumann et al., 1998). A lower proportion of domestic animal bones was also recovered at Saouga A compared to Oursi North (Linseele, 2007: 140), again making the case that availability of animal manure determined the amount of organic matter spread on the fields. It therefore seems highly likely that increased inputs of manure to arable fields were enabled by an increase in the number of livestock.

The $\delta^{15}N$ values of pearl millet grains from the early first millennium AD site of Oursi West are similar to those of modern pearl millet grains sampled from farming plots in northeast Senegal (–1.1 to 6.6 ‰) (see shaded area in Fig 3; values are taken from Styring et al., 2019). In Senegal, plots received low to medium levels of manure/household waste, either from compost heaps comprising household waste and manure from a few livestock kept within the homestead, through grazing of large herds of sheep/goats on the post-harvest cereal stubble, or through penning of cattle for a couple of months after harvest. The $\delta^{15}N$ values of pearl millet grains from Saouga A also fall within the range of pearl millet $\delta^{15}N$ values from

Senegal but are nonetheless higher than those from Oursi West ($t(45.7) = -3.26$, $p = .00211$, mean $\delta^{15}N$ value of samples from Oursi West = 5.2 ‰, mean $\delta^{15}N$ value of samples from Saouga A = 6.1 ‰) (Fig 3). These pearl millet fields likely received household waste/manure inputs similar to those plots in Senegal, suggesting that the manure needs at these two sites could have been met from *within* households which possessed a moderate number of small livestock.

The pearl millet grains from Oursi North, Oursi hu-beero and Kissi 3B generally had higher $\delta^{15}N$ values than the pearl millet sampled in Senegal (Fig 3). No modern analogue with such high $\delta^{15}N$ values has been studied thus far in West Africa. However, the increase in cereal grain $\delta^{15}N$ values with increased household waste/manure addition (Styring, Charles, et al., 2017) makes it likely that these pearl millet fields received higher inputs of manure than observed in Senegal, through access to more animal manure and greater quantity/frequency of its application. The very high $\delta^{15}N$ values of pearl millet grains from Oursi hu-beero (>8 ‰) have only been observed in farming situations involving highly intensive manuring, of 20+ tonnes manure per hectare (Styring, Charles, et al., 2017). It is possible that the sampling of pearl millet from discrete spatial contexts at Oursi hu-beero, rather than through arbitrary stratigraphic sampling, has selected some pearl millet grains deriving only from plots close to the homestead, which likely received higher quantities of organic matter (e.g. Prudencio, 1993).

In contrast to Oursi West and Saouga A, it seems unlikely that the manure needs at Oursi North and Oursi hu-beero could have been met from within households with small numbers of sheep and goats. As sedentary farmers it would have been difficult to sustain large numbers of livestock in a landscape that was becoming increasingly densely cultivated. Rather, it seems more likely that livestock and their manure came from *outside* the farming settlements, potentially in association with nomadic pastoralists. Oursi North and Oursi hu-beero, as well as Kissi, where a single pearl millet sample also had a relatively high $\delta^{15}N$ value, are located next to a *mare*, which would have provided an important source of water for livestock in the dry season and therefore an important convergence point for nomadic pastoralists. Indeed, Barral (1977) describes the presence of 10,000 zebu cattle at one point in the dry season around the banks of the Mare d'Oursi in 1972, demonstrating how likely it is that this permanent water source was also a focus for nomadic pastoralists in the second millennium AD. This congregation of huge numbers of livestock (especially if predominantly cattle) would have provided an opportunity for sedentary farmers to collect large quantities of manure for their fields. Other evidence consistent with the convergence of nomadic pastoralists and sedentary farmers at this time comes from the recovery of bones from sheep, goats and cattle of varied sizes at Oursi hu-beero. This points to two discreet populations of livestock having come together at the site, perhaps one belonging to sedentary farmers and one to nomadic pastoralists (Linseele, 2007).

5. Conclusions

The archaeobotanical and now nitrogen isotopic data suggest that farming in the early first millennium AD at Oursi West was small-scale and that the fertility of the cultivated plots was maintained by long fallow periods and perhaps small inputs of household waste/manure. With the increase in population and settlement density, fallow periods became shorter and addition of organic matter in the form of animal manure increased in importance in order to maintain soil fertility. At Saouga A in the second millennium AD, there is little evidence for intensive livestock grazing, likely due to the lack of a year-round source of water. The consequent lower availability of manure meant that land was left fallow for longer at Saouga A than at contemporary sites. At Oursi North and Oursi hu-beero, evidence for overgrazing and intensive manuring, likely due to large numbers of cattle converging at the nearby *mare* in the dry season, points to a potential specialisation of settled farmers and nomadic pastoralists, whose herds increased the availability of manure above that produced by local livestock. This novel combination of fruit/seed, charcoal, faunal and isotopic evidence has thus enriched our knowledge of past lifeways in West Africa and the findings of this study demonstrate the potential of this approach in contributing to ongoing debates such as the emergence of specialised pastoralism in this region.

This nitrogen isotopic analysis of archaeological pearl millet grains has shed light on the management of soil fertility in a region of West Africa over a period of 1400 years. This area, however, seems to have been relatively rural, where stable conditions allowed long-lived and uninterrupted habitation for almost 1500 years (Kahlheber, 2004: 223). In the future, it would be interesting to compare these isotopic results from northeast Burkina Faso with those from other areas of West Africa with more abundant resources or a more strategic position, such as the Inner Niger Delta and the Méma region of Mali. Here, there is evidence of craft specialisation and the development of commercial urban centres, which means that the focus was perhaps not on producing an agricultural surplus per se (McIntosh, 1998; Togola, 1996). It is therefore possible that strategies for meeting subsistence needs in these regions differed from the intensification of manuring and labour inputs that is evidenced at these sites in Burkina Faso.

Acknowledgements

Our sincere thanks go to Barbara Eichhorn for her help with identification and photography of the pearl millet grains. We would also like to thank Doris Bergman-Dörr and Dagmar Schneider at the Institut für Physische Geographie, Goethe-Universität Frankfurt am Main, for their assistance in bone collagen extraction. We are also grateful to Jens Fiebig and Sven Hofmann for their assistance in isotopic determinations at the Institut für Geowissenschaften, Goethe-Universität Frankfurt am Main. AS is funded by the Alexander von Humboldt Foundation.

References

Albert K-D, Löhr D and Neumann K (eds) (2004) *Mensch Und Natur in Westafrika*. Weinheim: Wiley-VCH Verlag.

Amundson R, Austin AT, Schuur EAG, et al. (2003) Global patterns of the isotopic composition of soil and plant nitrogen. *Global Biogeochemical Cycles* 17(1). DOI: 10.1029/2002GB001903.

Aranibar JN, Otter L, Macko SA, et al. (2004) Nitrogen cycling in the soil-plant system along a precipitation gradient in the Kalahari sands. *Global Change Biology* 10(3): 359–373. DOI: 10.1111/j.1365-2486.2003.00698.x.

Arbonnier M (2009) *Arbres, Arbustes et Lianes Des Zones Seches d'Afrique de l'Ouest*. Versailles: Ed. Quae, MNHN.

Barral H (1977) *Les Populations Nomades de l'Oudalan et Leur Espace Pastoral*. Paris: OSTROM.

Barros P de (1986) Bassar: a quantified, chronologically controlled, regional approach to a traditional iron production centre in West Africa. *Africa* 56(2): 152–174. DOI: 10.1017/S0001972000041553.

Bigga G and Kahlheber S (2011) From gathering to agricultural intensification: archaeobotanical remains from Mege, Chad Basin, NE Nigeria. In: Fahmy AG, Kahlheber S, and D'Andrea AC (eds) *Windows on the African Past: Current Approaches to African Archaeobotany*. Frankfurt am Main: Africa Magna Verlag, pp. 19–66.

Bogaard A, Fraser R, Heaton THE, et al. (2013) Crop manuring and intensive land management by Europe's first farmers. *Proceedings of the National Academy of Sciences* 110(31): 12589–12594. DOI: 10.1073/pnas.1305918110.

Borgerhoff Mulder MB, Bowles S, Hertz T, et al. (2009) Intergenerational wealth transmission and the dynamics of inequality in small-scale societies. *Science* 326(5953): 682–688. DOI: 10.1126/science.1178336.

Champion L and Fuller DQ (2018) New evidence on the development of millet and rice economies in the Niger River basin: archaeobotanical results from Benin. In: *Plants and People in the African Past*. Springer, Cham, pp. 529–547. DOI: 10.1007/978-3-319-89839-1_23.

Chirikure S (2013) The archaeology of African metalworking. *The Oxford Handbook of African Archaeology*. DOI: 10.1093/oxfordhb/9780199569885.013.0010.

Craine JM, Elmore AJ, Aidar MPM, et al. (2009) Global patterns of foliar nitrogen isotopes and their relationships with climate, mycorrhizal fungi, foliar nutrient concentrations, and nitrogen availability. *New Phytologist* 183(4): 980–992. DOI: 10.1111/j.1469-8137.2009.02917.x.

DeNiro MJ and Hastorf CA (1985) Alteration of $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios of plant matter during the initial stages of diagenesis: Studies utilizing archaeological specimens from Peru. *Geochimica et Cosmochimica Acta* 49(1): 97–115. DOI: 10.1016/0016-7037(85)90194-2.

Donfack P, Floret C and Pontanier R (1995) Secondary succession in abandoned fields of dry tropical northern Cameroon. *Journal of Vegetation Science* 6(4): 499–508. DOI: 10.2307/3236348.

FAO (1978) *China: Recycling of Organic Wastes in Agriculture*. Soils Bulletin. Rome: FAO.

Fick SE and Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*: 37(12): 4302–4315. DOI: 10.1002/joc.5086.

Fraser RA, Bogaard A, Heaton T, et al. (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. *Journal of Archaeological Science* 38(10): 2790–2804. DOI: 10.1016/j.jas.2011.06.024.

Fraser RA, Bogaard A, Charles M, et al. (2013) Assessing natural variation and the effects of charring, burial and pre-treatment on the stable carbon and nitrogen isotope values of archaeobotanical cereals and pulses. *Journal of Archaeological Science* 40(12): 4754–4766. DOI: 10.1016/j.jas.2013.01.032.

Fuller DQ (2000) The botanical remains. In: Insoll T (ed.) *Urbanism, Archaeology and Trade*. Oxford: Archaeopress, pp. 28–35.

Gallagher DE (1999) *Analysis of Seeds and Fruits from the Sites of Arondo and Ft. Senedebu, Senegal*. Senior Honors Thesis. Rice University.

Gallagher DE (2010) *Farming beyond the escarpment: society, environment, and mobility in precolonial southeastern Burkino Faso*. Ph.D. University of Michigan, Ann Arbor, United States. Available at: https://search.proquest.com/docview/305211001/abstract/901E3212803A4CC2PQ/1 (accessed 26 September 2017).

Gallagher DE, McIntosh SK and Murray SS (2018) Agriculture and wild plant use in the Middle Senegal River valley, c. 800 BC—1000 AD. In: Mercuri AM, D'Andrea AC, Fornaciari R, et al. (eds) *Plants and People in the African Past*. Cham: Springer Nature Switzerland AG, pp. 328–361. DOI: 10.1007/978-3-319-89839-1_16.

Gestrich N and MacDonald KC (2018) On the margins of Ghana and Kawkaw: four seasons of excavation at Tongo Maaré Diabal (AD 500-1150), Mali. *Journal of African Archaeology* 16: 1–30.

Gron KJ, Gröcke DR, Larsson M, et al. (2017) Nitrogen isotope evidence for manuring of early Neolithic Funnel Beaker Culture cereals from Stensborg, Sweden. *Journal of Archaeological Science: Reports* 14: 575–579. DOI: 10.1016/j.jasrep.2017.06.042.

Hahn-Hadjali K (1998) Les groupements végétaux des savanes du sud-est du Burkina Faso (Afrique de l'Ouest). *Etudes sur la Flore et la Végétation du Burkina Faso et des Pays Avoisinants* 3: 3–79.

Hall JB, Aebischer DP, Tomlinson HF, et al. (1996) *Vitellaria Paradoxa. A Monograph - School of Agricultural and Forest Sciences Publication Number 8*. Bangor: University of Wales.

Hobbie EA and Ouimette AP (2009) Controls of nitrogen isotope patterns in soil profiles. *Biogeochemistry* 95(2): 355–371. DOI: 10.1007/s10533-009-9328-6.

Höhn A (2005) Zur eisenzeitlichen Entwicklung der Kulturlandschaft im Sahel von Burkina Faso : Untersuchungen von archäologischen Holzkohlen. Available at: http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/3159 (accessed 3 November 2017).

Höhn A and Neumann K (2012) Shifting cultivation and the development of a cultural landscape during the Iron Age (0–1500 AD) in the northern Sahel of Burkina Faso, West Africa: Insights from archaeological charcoal. *Quaternary International* 249. Long-term perspectives on human occupation of tropical rainforests: 72–83. DOI: 10.1016/j.quaint.2011.04.012.

Kahlheber S (2004) *Perlhirse und Baobab: archäobotanische Untersuchungen im Norden Burkina Fasos*. Ph.D. Johann Wolfgang Goethe Universität, Frankfurt am Main.

Kahlheber S and Neumann K (2007) The development of plant cultivation in semi-arid West Africa. In: *Rethinking Agriculture: Archaeological and Ethnoarchaeological Perspectives*. One World Archaeology. Walnut Creek: Left Coast Press, pp. 320–346.

Klee M, Zach B and Neumann K (2000) Four thousand years of plant exploitation in the Chad Basin of northeast Nigeria I: The archaeobotany of Kursakata. *Vegetation History and Archaeobotany* 9(4): 223–237. DOI: 10.1007/BF01294637.

Krings TF (1980) *Kulturgeographischer Wandel in Der Kontaktzone von Nomaden Und Bauern Uim Sahel von Obervolta. Am Beispiel Des Oudalan (Nordost-Obervolta)*. Hamburger Geographische Studien. Hamburg: Ferdinand Hirt.

Le Houérou HN (1989) *The Grazing Land Ecosystems of the African Sahel*. Ecological Studies (Analysis and Synthesis). Berlin: Springer.

Lespez L, Le Drezen Y, Garnier A, et al. (2011) High-resolution fluvial records of Holocene environmental changes in the Sahel: the Yamé River at Ounjougou (Mali, West Africa). *Quaternary Science Reviews* 30(5): 737–756. DOI: 10.1016/j.quascirev.2010.12.021.

Linseele V (2007) *Archaeofaunal Remains from the Past 4000 Years in Sahelian West Africa: Domestic Livestock, Subsistence Strategies and Environmental Changes*. BAR International Series 1658. Oxford: Archaeopress.

MacDonald K (2013) Complex societies, urbanism, and trade in the western Sahel. In: Mitchell P and Lane P (eds) *The Oxford Handbook of African Archaeology*. Oxford: Oxford University Press, pp. 829–844. Available at: http://ezproxy-prd.bodleian.ox.ac.uk:2067/view/10.1093/oxfordhb/9780199569885.001.0001/oxfordhb-9780199569885-e-57 (accessed 26 September 2018).

Magnavita S (2006) *1500 Jahre am Mare de Kissi. Eine Fallstudie zur Besiedlungsgeschichte des Sahel von Burkina Faso*. Ph.D. J. W. Goethe University, Frankfurt am Main.

Magnavita S (2013) Initial encounters: seeking traces of ancient trade connections between West Africa and the wider world. *Afriques. Débats, méthodes et terrains d'histoire* (04). DOI: 10.4000/afriques.1145.

Maurer A-F, Person A, Tütken T, et al. (2014) Bone diagenesis in arid environments: An intra-skeletal approach. *Palaeogeography, Palaeoclimatology, Palaeoecology* 416(Supplement C): 17–29. DOI: 10.1016/j.palaeo.2014.08.020.

McIntosh RJ (1998) *The Peoples of the Middle Niger: The Island of Gold*. Oxford: Blackwell Publishing Ltd.

McIntosh SK (1994) Changing perceptions of West Africa's past: archaeological research since 1988. *Journal of Archaeological Research* 2(2): 165–198.

McIntosh SK (1995) Palaeobotanical and human osteological remains. In: McIntosh SK (ed.) *Excavations at Jenné-Jeno, Hambarketolo, and Kaniana (Inland NIger Delta, Mali), the 1981 Season*. Berkeley, US: University of California Press, pp. 348–359.

Murray MA, Fuller DQ and Capezza C (2007) Crop production on the Senegal River in the early first millennium AD: preliminary archaeobotanical results from Cubalel. In: Cappers RTJ (ed.) *Fields of Change: Progress in African Archaeobotany*. Barkhuis.

Murray SS (2005) Recherches archéobotaniques. In: Bedaux R, Polet J, Sanogo K, et al. (eds) *Recherches Archéologiques à Dia Dans Le Delta Intérieur Du Niger (Mali): Bilan Des Saisons de Fouilles 1998–2003*. Leiden: CNWS Publications, pp. 386–400.

Murray SS (2008) A report on the charred botanical remains from Sincu Bara, a mid-first millennium AD Middle Senegal Valley site. *Nyame Akuma* 69: 56–63.

Neumann K (2018) Development of plant food production in the West African savannas: archaeobotanical perspectives. *Oxford Research Encyclopedia of African History*. DOI: 10.1093/acrefore/9780190277734.013.138.

Neumann K, Kahlheber S and Uebel D (1998) Remains of woody plants from Saouga, a medieval west African village. *Vegetation History and Archaeobotany* 7(2): 57–77.

Nitsch E, Andreou S, Creuzieux A, et al. (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 Archaeology* 49(1): 105–137. DOI: 10.1080/00438243.2016.1271745.

Nixon S, Murray MA and Fuller DQ (2011) Plant use at an early Islamic merchant town in the West African Sahel: the archaeobotany of Essouk-Tadmakka (Mali). *Vegetation History and Archaeobotany* 20(3): 223–239. DOI: 10.1007/s00334-010-0279-6.

Oates J, McMahon A, Karsgaard P, et al. (2007) Early Mesopotamian urbanism: a new view from the north. Available at: http://antiquity.ac.uk/ant/081/ant0810585.htm (accessed 13 September 2013).

Otto T and Delneuf M (1998) Evolution des ressources alimentaires et de paysages au nord du Cameroun: Apport de l'archéologie. In: Chastenet M (ed.) *Plantes et Paysages d'Afrique*. Paris: Karthala, pp. 491–514.

Pelissier P (1966) *Les Paysans Du Senegal*. Saint-Yrieux, France: Imprimerie Fabregue.

Petit LP and Czerniewicz von M (2011) Oursi-hu-beero in situ. In: Petit LP, Czerniewicz von M, and Pelzer C (eds) *Oursi Hu-Beero. A Medieval House Complex in Burkina Faso, West Africa*. Leiden: Sidestone Press, pp. 31–34.

Prudencio CY (1993) Ring management of soils and crops in the west African semi-arid tropics: The case of the mossi farming system in Burkina Faso. *Agriculture, Ecosystems & Environment* 47(3): 237–264. DOI: 10.1016/0167-8809(93)90125-9.

Pullan RA (1974) Farmed parkland in West Africa. *Savanna* 3: 119–151.

Reid REB, Lalk E, Marshall F, et al. (2018) Carbon and nitrogen isotope variability in the seeds of two African millet species: Pennisetum glaucum and Eleusine coracana. *Rapid Communications in Mass Spectrometry* 32(19): 1693–1702. DOI: 10.1002/rcm.8217.

Serneels V (2017) The massive production of iron in the Sahelian belt: Archaeological investigations at Korsimoro (Sanmatenga – Burkina Faso). *Materials and Manufacturing Processes* 32(7–8): 900–908. DOI: 10.1080/10426914.2016.1244842.

Styring AK, Rösch M, Stephan E, et al. (2017) Centralisation and long-term change in farming regimes: comparing agricultural practices in Neolithic and Iron Age south-west Germany. *Proceedings of the Prehistoric Society* 83: 357–381.

Styring AK, Charles M, Fantone F, et al. (2017) Isotope evidence for agricultural extensification reveals how the world's first cities were fed. *Nature Plants* 3: 17076. DOI: 10.1038/nplants.2017.76.

Styring AK, Diop AM, Bogaard A, et al. (2019) Nitrogen isotope values of *Pennisetum glaucum* (pearl millet) grains: towards a reconstruction of past cultivation practices in the Sahel, West Africa. *Vegetation History and Archaeobotany*. DOI: https://doi.org/10.1007/s00334-019-00722-9.

Szpak P, Metcalfe JZ and Macdonald RA (2017) Best practices for calibrating and reporting stable isotope measurements in archaeology. *Journal of Archaeological Science: Reports* 13(Supplement C): 609–616. DOI: 10.1016/j.jasrep.2017.05.007.

Togola T (1996) Iron Age occupation in the Méma region, Mali. *African Archaeological Review* 13(2): 91–110. DOI: 10.1007/BF01956303.

Toutain B (1980) Le rôle des ligneux pour l'élevage dans les régions soudaniennes de l'Afrique de l'Ouest. In: Le Houérou HN (ed.) *Browse in Africa: The Current State of Knowledge*. Addis Ababa: ILCA, pp. 102–108.

Vaiglova P, Bogaard A, Collins M, et al. (2014) An integrated stable isotope study of plants and animals from Kouphovouno, southern Greece: a new look at Neolithic farming. *Journal of Archaeological Science* 42: 201–215. DOI: 10.1016/j.jas.2013.10.023.

Vaiglova P, Snoeck C, Nitsch E, et al. (2014) Impact of contamination and pre-treatment on stable carbon and nitrogen isotopic composition of charred plant remains. *Rapid communications in mass spectrometry: RCM* 28(23): 2497–2510. DOI: 10.1002/rcm.7044.

van Klinken GJ (1999) Bone collagen quality indicators for palaeodietary and radiocarbon measurements. *Journal of Archaeological Science* 26(6): 687–695. DOI: 10.1006/jasc.1998.0385.

Vignola C, Masi A, Balossi Restelli F, et al. (2017) $\delta^{13}C$ and $\delta^{15}N$ from ^{14}C-AMS dated cereal grains reveal agricultural practices during 4300–2000 BC at Arslantepe (Turkey). *Review of Palaeobotany and Palynology* 247(Supplement C): 164–174. DOI: 10.1016/j.revpalbo.2017.09.001.

Vogelsang R, Albert K-D and Kahlheber S (1999) Le sable savant: les cordons dunaires sahéliens au Burkina Faso comme archive archéologique et paléoécologique du Holocène. *Sahara* 11: 51–60.

Supporting Information Captions

Table S1. Contextual details of archaeological pearl millet grain samples from sites in northeast Burkina Faso.

Fig S1. Fourier-transform infrared spectroscopy spectra of archaeological pearl millet grain samples from Kissi 3 and Oursi hu-beero, northeast Burkina Faso.

Table S2. Nitrogen and carbon content and $\delta^{15}N$ and $\delta^{13}C$ values obtained by EA-IRMS analysis of standards and archaeological pearl millet grains from sites in northeast Burkina Faso.

Table S3. Standard uncertainty calculator for two sessions of EA-IRMS analysis.

Table S4. Archaeological contexts and results of collagen extraction of archaeological animal bones from northeast Burkina Faso.