A ‘long-burning issue’: comparing woody resource use for ironworking in three major iron smelting centres of sub-Saharan Africa

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‘Everything has its limit – iron ore cannot be educated into gold.’ (Mark Twain)

For a number of years, during which I studied the anthracology of rock shelters in north-western Namibia for my PhD thesis, I shared a room – microscopy lab and office in the meantime – with Ulla Tegtmeier, my always reliable, good and calm colleague. Though our research areas were definitely far apart from a geographical point of view, we shared a special ‘passion’: the detective work of identifying and interpreting wood charcoal assemblages from archaeological sites – a task which, though superficially dusty and not very exciting, can keep your mind very busy… (Barbara Eichhorn, January 2019)

Zusammenfassung – Die traditionelle Eisenmetallurgie des subsaharischen Afrika wurde und wird in der Literatur häufig mit ökologischer Degradation in Verbindung gebracht, insbesondere durch eine vermeintliche Übernutzung von Holz als Brennstoff für den Betrieb der Schmelzöfen. Diese negative Einschätzung erfolgt weitgehend unabhängig von den sehr unterschiedlichen ökologischen Rahmenbedingungen, unter denen Eisenverhüttung in Afrika stattfand, obwohl mit diesen eine hohe Variabilität der nutzbaren natürlichen Ressourcen und eine unterschiedliche Resilienz der Gehölzvegetation gegenüber Holzentnahme einhergeht. Um eine differenziertere Betrachtung zu erreichen, vergleichen wir in diesem Beitrag unsere anthrakologischen Ergebnisse von drei bedeutenden Zentren traditioneller afrikanischer Eisenproduktion (Fiko Tradition, Mali; Bassar, Togo; Meroe-Region, Sudan). Unabhängig von den jeweils vorherrschenden Umweltbedingungen wurde für die Verhüttung überwiegend Holz mit hoher Dichte verwendet. Allerdings zeichnet sich nur in der Meroe-Region eine extreme Selektivität für eine einzelne Baumart ab, während in Westafrika ein breiteres Spektrum von Gehölztaxa zum Einsatz kam. Neben der tatsächlichen Qualität als Brennstoff haben mit hoher Wahrscheinlichkeit kulturelle Präferenzen die Wahl der Gehölzarten beeinflusst.

Der Brennstoffbedarf der westafrikanischen Fundplätze wurde überwiegend aus der zonalen Vegetation, insbesondere aus den umliegenden Agroforstsystemen, gedeckt. Im Gegensatz dazu scheinen in der ariden Meroe-Region die extrazonalen *Acacia nilotica*-Bestände des Niltals eine stabile und zuverlässige Brennstoffversorgung ermöglicht zu haben. An den westafrikanischen Fundplätzen belegen die Holzkohleanalysen Veränderungen der Gehölzvegetation im Laufe der Zeit. Die Brennstoffgewinnung für die Eisenverhüttung war jedoch nur einer von zahlreichen Faktoren, die die regionale Gehölzvegetation während der späten Eisenzeit beeinflussten. Die Ausweitung des Ackerbaus und die Veränderung der landwirtschaftlichen Praktiken, die mit der generellen Verfügbarkeit von Eisen einhergingen, verstärkten die Auswirkungen der Holzentnahme für die Eisenherstellung und andere Zwecke.

Schlüsselwörter – Westafrika, Meroe, Metallurgie, Brennstoff, Holzkohle, Phytolithe

Abstract – Ancient sub-Saharan iron metallurgy has often been blamed for triggering ecological deterioration, above all by a presumed over-exploitation of wood for operating the fuel-thirsty smelting furnaces. This assessment is largely negative, regardless of the different natural environments where iron smelting took place, and thus in spite of the variability of provided ecosystem services and differing resilience to wood exploitation. We argue for a more differentiated view of the impacts of traditional African iron smelting, respecting the fact that wood is a renewable resource and bearing the dissimilarity of exploitable resources in mind. Summarizing our previous research, we compare the anthracological results which we obtained at three major iron smelting centres (Fiko Tradition, Mali; Bassar, Togo; the Meroe area, Sudan). Regardless of the prevailing environmental conditions, the predominant use of high density wood is striking. However, only in the Meroe area is extreme selectiveness of a single species evident, whereas in the West African iron smelting centres a wide array of woody taxa has been used. In addition to fuel quality, cultural preferences probably controlled the choice of species.

Fuel provision in Fiko and Bassar was mainly based on the exploitation of zonal vegetation, particularly the agroforestry systems surrounding the sites. In contrast, the extrazonal *Acacia nilotica* woodlands of the Nile River valley seem to have provided a stable and reliable fuel supply in the arid Meroe area. At the West African sites, the anthracological records point to vegetation changes over the course of time. However, we consider fuel exploitation for iron smelting as only one among multiple causal factors affecting the regional woody vegetation during the Late Iron Age. The expansion of arable land and changing agricultural practices due to the general availability of iron agricultural tools intensified the effects of wood exploitation, for iron production and various other purposes, on the tree cover.

Keywords – West Africa, Meroe, metallurgy, fuel, wood charcoal, phytoliths

Introduction

In sub-Saharan Africa, prehistoric and historic iron metallurgy has often left tremendous traces in the landscape, comprising slag heaps of sometimes enormous sizes, furnace wall and tuyère remains and, from time to time, even entirely preserved smelting furnaces (**fig. 1**). From early on, this particular technological heritage deeply impressed voyagers and scientists, often leading

Fig. 1 Tatré (Bassar area Togo), ancient bloomery furnace.

them to compare major African ironworking sites with metallurgy at an industrial scale in Europe. As examples, the famous Royal City of Meroe in Sudan's Nile Valley was referred to as the *'Birmingham of ancient Africa'* (Sayce 1912, 55), whereas J. P. Warnier and I. Fowler (Warnier/Fowler 1979) characterised iron smelting in three villages of the Ndop Plain in western Cameroon as a *'19th Ruhr in Central Africa'*. Almost inevitably, in the further course of observations and descriptions of large-scale African iron metallurgy, the question of its ecological effects repeatedly arose. Iron smelting admittedly requires a lot of fuel, and as most of the known traditional African ironworking operated with wood charcoal or, rarely, with fresh wood (cf. Celis 1991, 24), a more or less dramatic over-exploitation of woody resources has repeatedly been assumed, often simply designated as 'deforestation' (e. g. Haaland 1980; idem 1985; Shaw 1981; Goucher 1981; idem 1986; De Barros 1986; Herbert/Goucher 1987; Pinçon 1990; Celis 1991; Kense/Okoro 1993; Okafor 1993; Hahn 1997; Thompson/Young 1999; Pelzer et al. 2004; Willis et al. 2004; Bayon et al. 2012; Garcin et al. 2018; Malhi 2018). However, assessing the effects of wood exploitation for iron smelting on the vegetation requires: 1. considering that various natural environments where iron metallurgy was practiced may offer quite different exploitable natural resources; 2. taking into account the ability of biomass to regenerate in general; and 3. bearing in mind that huge slag accumulations were not built up from one day to the next, but more often reflect repeated smelting processes through a long period of production. The latter fact 'reduces' the relative amounts of debris accumulated per individual smelting process or per year, and thus the respective produced mass of iron and exploited woody biomass requirements.

In a number of previous publications (Eichhorn 2012; Eichhorn et al. 2013a; Eichhorn et al. 2013b; Eichhorn/Neumann 2014; Robion-Brunner/Eichhorn 2016; Serneels et al. 2016; Eichhorn/Robion-Brunner 2017; Garnier et al. 2018; Humphris/Eichhorn 2019) we pursued, on the one hand, the rationale behind fuel selection for iron smelting at a number of iron metallurgy sites situated in different ecological zones of sub-Saharan Africa and, on the other hand, questions regarding the sustainability of wood use at larger-scale sites. This article summarizes and compares the results of our anthracological research at three major iron smelting centres, with the aim to demonstrate the variability of woody resource exploitation and possible resource management strategies, but also in order to discuss the feasibility of assessing the respective ecological impacts of wood exploitation for large-scale iron smelting respecting the various environmental settings. The first one of these centres comprises the site complexes of the 'Fiko Tradition', situated at the western margin of the Dogon Country in Mali; the second is found in the northern region of the Bassar area in Central Togo, long renowned for intensive metallurgy; and the third is the famous Royal City of Meroe with the neighbouring Meroitic town of Hamadab.

For each of these metallurgical centres, all characterised by long-term histories of iron smelting and significant iron output, we will refer to the matter of exploitable woody resources in terms of available taxa and potential reproductive capacity of the woody vegetation surrounding the sites. We will also refer to the question of a selective or random choice of taxa as fuel, as it can be deduced from the actual charcoal analytical results. Based on the individual site chronologies and the particular environmental conditions, we will critically discuss if wood exploitation for iron metallurgy likely happened on a sustainable basis, or had indeed the destructive effects

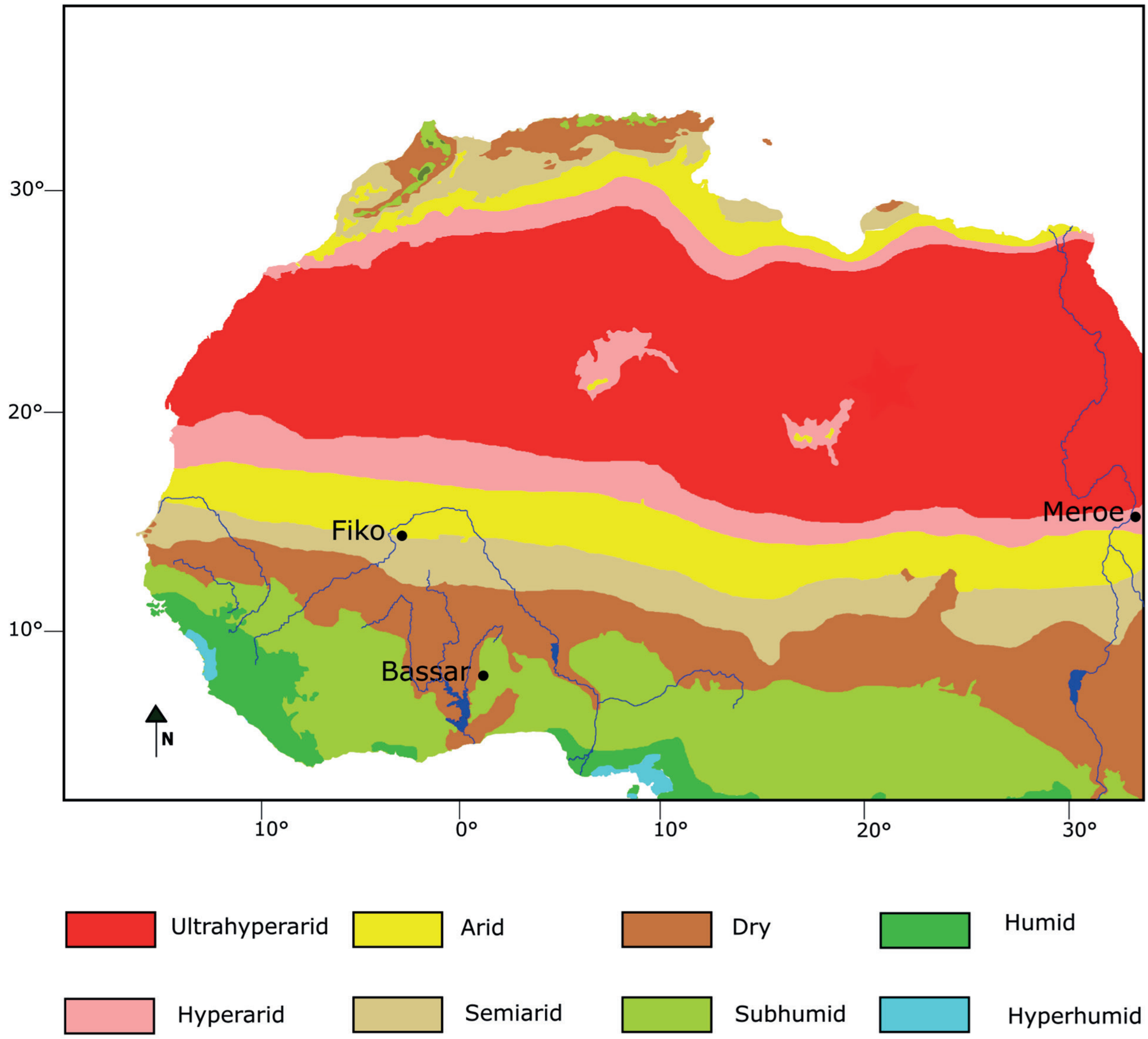

Fig. 2 Map showing the location of the sites in relation to bioclimate (ombrotypes).

on the woody vegetation which were formerly presumed.

The ancient iron smelting sites and their natural environment

Fiko tradition sites

The first study area comprises the sites of the 'Fiko tradition' (**fig. 2**), located at the western margin of the Dogon Plateau in Mali, adjacent to the *Macina* or Inland Niger Delta. The iron smelting sites are distributed over about 450 km^2 and consist of eight iron smelting networks on both sides of the Yamé River. They are characterised by very large dumps of metallurgical waste which form irregular or closed craters, in general several meters high and building up around single or paired bloomery furnaces (**fig. 3–5**; Robion-Brunner et al. 2013). On the basis of intensive archaeological prospecting and topographical mapping, the total amount of metallurgical waste of all Fiko tradition sites could be assessed at 225 000 m^3 to 300 000 m^3 (Robion-Brunner 2010). Two examples illustrate the complex history of Fiko tradi-

Fig. 3 Crater-shaped slag heaps at Fiko, top view.

tion iron smelting. Around the abandoned village of Kéma-Gumbessugo a number of working areas could be identified, each one made up of several metallurgical waste heaps close to one another (Eichhorn 2012, fig. 2). The presumably oldest preserved heaps (ironworking sector 8) are situated on a sandstone hill and nestle closest to the abandoned village, while sectors 5, 6 and 7 are located on different terraces. The most recent heaps (sectors 1, 2 and 3) are situated on the plain, directly in front of the sandstone hill. According to oral traditions, Kéma-Gumbessugo was raided by warriors of the Ségou Kingdom. Therefore the abandonment of the village and its iron production sites has cautiously been dated to the 18th century. Oral traditions have conveyed a history of displacement, the founding of a new village, Kéma-Koundiouli on the other side of the Yamé River and, later, of the present village Kéma, each with corresponding iron smelting workshops (Huysecom et al. 2009). The second example is the site of Fiko (Huysecom et al. 2004; Huysecom et al. 2005; Huysecom et al. 2009), where the largest and oldest slag heap is situated on sandstone terraces near the present village, while later iron production continued on the plain until the last century. In order to establish the chronology more firmly, twenty-four radiocarbon dates have been obtained from Fiko tradition sites (Eichhorn 2012; Eichhorn et al. 2013b). A single date at Fiko indicates that metallurgical activities date as far back as ca. 600 AD, followed by one date around 800 AD at Kowa, whereas all other dates indicate intensive and probably continuous production during the past millennium. In contrast to the oral tradition, radiocarbon dating indicates that iron smelting at the present-day village Kéma started before Kéma-Gumbessugo or Kéma-Koundiouli were abandoned. Fiko tradition iron smelting finally ceased in the early 20th century AD. The metallurgical activities have been characterised as near-industrial and the iron production levels seem to have exceeded local or even regional needs distinctly. It is likely that the produced iron was distributed outside the Dogon Country, presumably in the Inland Niger Delta (Robion-Brunner et al. 2013).

According to the Köppen-Geiger classification system, the region features a hot steppe climate (Bsh, **fig. 6**; Kottek et al. 2006). With a rainy season of three and a half months precipitation is strictly

Fig. 4 Crater-shaped slag heaps at Fiko, lateral view.

seasonal and reaches mean annual values of about 500 mm (Nouaceur 2001). Phytogeographically, this area is situated in the transitional zone between the Sahelian and Sudanian zones, specifically at the limit of the Sudanian *Adansonia digitata-Bombax costatum* savannas and Sahelian *Combretum glutinosum* savannas (Granier 2001). P. Jaeger and D. Winkoun (Jaeger/Winkoun 1962) described the natural vegetation of favourable sites on the Dogon Plateau as a diverse Sudanian savanna. However, at present, a typical West African cultural landscape covers the Dogon Plateau and the adjacent plains. This landscape is mainly characterised by cultivated agroforestry parklands with few, consciously selected useful tree species which either bear edible fruits or have soil-fertilizing capacities. In addition, typical fallow shrub and tree species with the ability to regenerate from suckers after cutting dominate the woody vegetation. The charcoal assemblages from the nearby Ounjougou site complex indicate that, during long periods of the Holocene, a gallery forest characterised by the extrazonal occurrence of Sudano-Guinean species (species today restricted to areas further south with higher precipitation), grew along the Yamé River which ran close to the metallurgical sites. The surrounding savannas were in the past probably also characterised by the occurrence of these species (Ozainne et al. 2009; Lespez et al. 2011; Eichhorn/Neumann 2014). At present, the gallery forest has almost vanished and is floristically impoverished, probably due to Late and Terminal Holocene climatic deterioration, going hand in hand with increasing anthropogenic impact. Only a few of the Sudano-Guinean species such as *Cola laurifolia* (**fig. 7**) still persist in floristically more diversified ravine forests at the escarpment of the Dogon Plateau (Jaeger/Winkoun 1962; Eichhorn/Neumann 2014).

Bassar

Our second study area, in northern Bassar (**fig. 2**), is part of another major centre of West African iron production, located in Central Togo around the town of the same name. The onset of Bassar iron smelting is considered to date back as far as 400–200 BC (De Barros 2012; idem 2013). The metallurgists of this time seem to have used very small furnaces with mechanical ventilation. This

Fig. 5 Huge slag heap at Kéma-Gumbessougou.

early evidence is followed by an apparent hiatus of a millennium (De Barros 2013). The introduction of induced draft furnaces at the end of the 13th century AD resulted in profound changes of Bassar iron production levels. Induced draft furnaces are ventilated via natural draft powered by the chimney (or stack) effect, requiring no bellows and therefore less labour. The introduction of the induced draft furnaces intensified production significantly and iron was traded to neighbouring West African societies (Martinelli 1982; De Barros 1985; idem 1986). From the 16th century onwards, iron production operated on a supra-regional scale, still expanding in the 19th century and eventually declining in the 20th century. Concerning our era, P. De Barros (De Barros 1986) proposed the division of the Bassar iron industry into four distinct periods: Period 1 (ca. late 1st millennium AD to 1300/1350 AD) classified as small-scale production for mainly local needs; Period 2 (ca. 1300/1350 AD to 1550/1600 AD) categorised as significant local production; Period 3 (ca. 1550/1600 AD to ca. 1800 AD) witnessing large-scale production for supra-regional export; and finally, Period 4 (ca. 1800 AD to 1905 AD and 1925 AD in the eastern and western parts of the research area, respectively) characterised by expanding production, disruption, and the eventual decline of Bassar metallurgy.

The Bassar region is situated at the transition of Sudanian savannas and southern Sudanian dry forests (Brunel 1981). According to the Köppen-Geiger system, the climate is characterised as equatorial winter-dry savanna climate (Aw, Kottek et al. 2006). Similar to the Fiko area, the climatic regime is distinctly seasonal, but with a longer rainy season lasting from April to October and higher mean precipitation values, amounting to about 1 200–1 400 mm annually (**fig. 6**; Gu-Konù 1981; Kouami et al. 2009; De Barros 2013). The current vegetation on the plains has been strongly transformed by human impact and consists mainly of agroforestry parklands made up of fields and fallows with protected fruit trees, particularly the shea butter tree (*Vitellaria paradoxa*) and the néré tree (*Parkia biglobosa*), as well as the re-growth of trees and shrubs which were cut when preparing the fields. Annual burning of the grass layer and of the fields is practised (**fig. 8**). The hills and mountains are at present not cultivated, but grazed and browsed by livestock and, particularly in proximity to settlements, subject to intensive woodcutting for fuel and other household purposes (**fig. 9**).

	Meroe and Hamadab	Fiko tradition sites	Northern Bassar area
Köppen-Geiger climate classification	Bwh	Bsh	Aw
Mean annual precipitation	<70 mm	Ca. 500 mm	1200-1400 mm
Zonal vegetation	Semidesert vegetation	Northern Sudanian savannas and agro-forestry parklands	Southern Sudanian savannas and agro-forestry parklands
Extrazonal vegetation of rivers and wetlands	Nile floodplain with gallery forests, particularly on natural levees (cf. Wolf et al. 2014; Wolf 2015)	Floristically impoverished gallery forest of the Yamé River; ravine forests	Gallery forest of the seasonal Tatré River
Number of identified charcoal types within metallurgical contexts	8	>30	22

Fig. 6 Characteristics of the three research areas.

Fig. 7 *Cola laurifolia* in fruit, Bandiagara Escarpment ravine forest (Mali).

Meroe and Hamadab

Our third study area, the ancient city of Meroe (**fig. 2**), situated between the 5th and 6th Nile cataracts in Sudan, is particularly famous for its impressive remains of ancient iron production (**fig. 10**), which led to the early description that *"Meroë, in fact, must have been the Birmingham of ancient Africa; the smoke of its iron-smelting furnaces must have been continually going up to heaven, and the whole of northern Africa might have been supplied by it with implements of iron"* (Sayce 1912, 55), and to decades of speculations about the potential local, regional and international significance of the iron industries at Meroe (summarized in Humphris/Rehren 2014). By the early 3rd century BC, the primary royal city of Kush had shifted from Napata near the 4th Cataract of the Nile south to Meroe, from where Kushite royals ruled until the 4th century AD (for an overview of Kushite history see Welsby 1996; Török 1997; idem 2015; Edwards 2004). Although already renowned as

Fig. 8 Bushfire in the Bassar area (Togo).

Fig. 9 Hillside near Belemele, subject to intensive wood cutting (Bassar area, Togo).

Fig. 10 Meroe's largest slag heap MIS4 under excavation in 2016.

an intensive ancient iron production centre (e. g. Trigger 1969; Tylecote 1970; idem 1982; Shinnie 1985; Rehren 2001), current archaeometallurgical research at Meroe and the nearby site of Hamadab, including the systematic investigation of a number of slag heaps across the two sites, as well as an intensive experimental archaeology investigation, has provided significant new insights into the chronology and technology of Kushite iron production (Humphris 2014; Humphris/Carey 2016; Humphris/Scheibner 2017; Ting/Humphris 2017; Humphris et al. 2018a; Humphris et al. 2018b). It is now known that iron metallurgy, sometimes on a significant scale, was practiced at Meroe for more than 1 000 years from potentially at least the 7th–6th century BC. Meroe is therefore among Africa's longest lived and possibly most ancient iron production centres (Humphris/Scheibner 2017).

The climate of the region is classified as a hot desert climate (Bwh, **fig. 6**; Kottek et al. 2006), and the area receives only about 70 mm of annual rainfall which is almost exclusively restricted to the summer months. Sparse semi-desert vegetation with the tree species *Acacia tortilis* ssp. *raddiana, Maerua crassifolia* and *Balanites aegyptiaca* characterises the zonal sites fully depending on the July to September rains, whereas extrazonal wetland vegetation is lusher. In the floodplain, it comprises acacia alluvial forests and tamarisk bushes while river banks are characterised by in places dense vegetation with *Acacia nilotica*, *Acacia seyal*, and *Faidherbia albida*, indicating the maximum flood level. Pioneer vegetation, such as *Tamarix nilotica* communities, profits from residual moisture after flooding (Wolf et al. 2014).

Main results from our previous anthracological studies

Fiko tradition sites

Throughout the entire known chronology of Fiko tradition iron smelting, a relatively wide array of woody species was exploited for fuel for iron technology (Eichhorn et al. 2013b, fig. 4–5). More than 30 different wood anatomical types were identified in total. This cannot be directly translated into numbers of tree or shrub species, as in tropical African anthracology most of the identified anatomical types do not represent a single botanical species, but may include several species which cannot be securely distinguished on the basis of wood anatomy, either of one genus, as in the case of *Terminalia* spp. or even on a higher taxonomic rank such as subfamily or family (cf. Hubau et al. 2012; Ekblom et al. 2014; Eichhorn/Robion-Brunner 2017; Höhn/Neumann 2018). Both the dispersed charcoal assemblages from the slag heaps at the different sites, as well as the charcoal directly retrieved from slag blocks at Kéma, indicate this diversity of taxa used as fuel for iron smelting.

Generally the charcoal assemblages reasonably well reflect the Sudanian woody vegetation close to the limit of the Sahel typical for the area. However, a few taxa are distinctly dominant across most of the charcoal assemblages, namely *Prosopis africana* (Fabaceae), the *Terminalia* species (Combretaceae), the Sapotaceae and *Pterocarpus lucens* (Fabaceae), followed by other members of the Combretaceae family (Eichhorn 2012; Eichhorn et al. 2013a; Eichhorn et al. 2013b; Eichhorn/Neumann 2014; Robion-Brunner/Eichhorn 2016). These taxa are all important constituents of the surrounding savannas, fields and fallows. A number of other typical species of the area, specifically many which are typical useful trees of the currently prevailing agroforestry parks, are much lesser represented. The charcoal assemblages in all samples are distinctly dominated by trees and shrubs with dense wood, whereas species with a low wood density (e. g. from the families Anacardiaceae, Burseraceae, Moraceae, Verbenaceae, Sterculiaceae and Bombacaceae) are hardly represented, although these species are quite common in the agroforestry parks and savannas of the area.

In the course of time, from ca. the 12th/13th century AD until the abandonment of iron smelting in the 20th century AD, there are distinct changes in the sequence of Fiko which concern the abundance of the dominant taxa. *Terminalia* spp. and *Prosopis africana* which were preferred in the beginning decrease, whereas *Combretum glutinosum* and *Pterocarpus* cf. *lucens* increase significantly. The shea butter tree (*Vitellaria paradoxa,* Sapotaceae), a typical useful species of Sudanian agroforestry parks, is also increasingly used, and some Sudanian species are gradually replaced by Sahelian trees and shrubs requiring less precipitation. The analyses conducted at the Kéma complex show less unambiguous changes. A similar decrease of preferred taxa and the increase of species able to regenerate after cutting became evident when we compared the data available for sector 7 and the more recent sector 2 of Kéma-Gumbessugo. However, data from sector 1, which according to AMS-dating still operated during the past 300 years, indicate that the most preferred taxa were still (or again) sufficiently available to be highly represented in the charcoal assemblage. The oral traditions indicate several movements and displacement of iron smelting workshops to the other side of the Yamé River. It is conceivable that this repeated displacement allowed for the recurrent exploitation of formerly more or less unaltered woody vegetation and the regeneration of exploited stocks of woody plants after the abandonment of workshops.

Northern Bassar

Concerning the representation of taxa in the charcoal assemblages there are clear similarities between the two West African sites under consideration. Comparable to the Fiko tradition sites, a considerable multitude of woody taxa was used for iron smelting in northern Bassar. In total, 22 wood anatomical types were identified at the site complexes of Tchogma and Tatré. Likewise, all analysed charcoal samples are, regardless of site and production period, dominated by a few charcoal types, representing a restricted number of woody taxa only (Eichhorn/Robion-Brunner 2017, fig. 3–4): The *Prosopis africana* type, *Pericopsis* spp., Caesalpinioideae undifferentiated, and the Sapotaceae occur with both the highest steadiness and relative frequencies. The *Prosopis africana* type, abundant at Bassar as well as the Fiko sites, most probably represents a single species, which is a Sudano-Guinean savanna tree that is highly valued by blacksmiths and metallurgists in many parts of West Africa (e. g. Burkill 1995, 259; Arbonnier 2002, 394; Kiethéga 2009, 249–257). In the Bassar case and at the Fiko tradition sites, the Sapotaceae type probably represents the shea butter tree *Vitellaria paradoxa* (for a differential diagnosis see Eichhorn/Robion-Brunner 2017, 163; 173). This species is one of the most dominant constituents of the present regional agroforestry parklands (Wala et al. 2005; own field observations 2014). In Burkina Faso, the shea butter tree is most often mentioned as being suitable for iron smelting fuel and its wood is among the most important firewood species in the south-east of the country (Kiethéga 2009, 249–257; Gallagher 2010, tab. 3.5). *Pericopsis* spp. (in the research area this wood anatomical type is represented by a single species, *P. laxiflora*) and Caesalpinioideae undifferentiated found at Bassar have also been identified in iron smelting sites in the northern Ivory Coast (Serneels et al. 2016). *Pericopsis laxiflora* wood makes excellent charcoal (Burkill 1995, 418). This species occurs in savannas, at the edges of gallery forest, and in fallows (Arbonnier 2002, 323). In the Bassar area, it is a vigorously re-sprouting shrub or small tree found on fallows and at the foot of hills, and is often subjected to wood-cutting (own observations 2014). The type Caesalpinioideae undifferentiated is comprised of a number of species which cannot be distinguished on the basis of their wood anatomy. Among others, this type also comprises *Burkea africana*, which is, according to our ethnohistorical interviews in the Bassar area, one of the few tree species yielding highly estimated fuel for iron smelting (Eichhorn/Robion-Brunner 2017, tab. 3). *B. africana* is a Sudano-Guinean savanna tree whose wood is exploited for firewood and charcoal, the latter

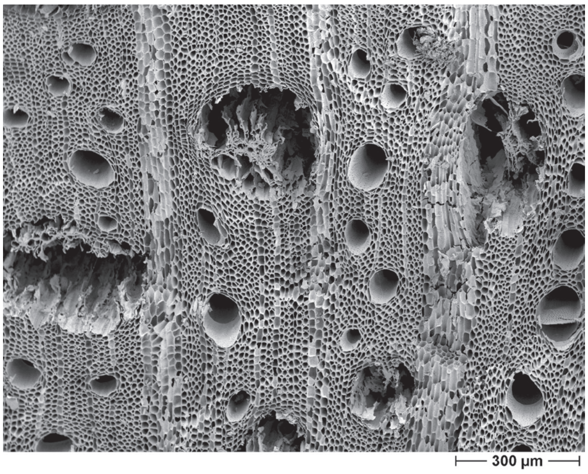

Fig. 11 *Leptadenia pyrotechnica* wood charcoal, transverse section, SEM.

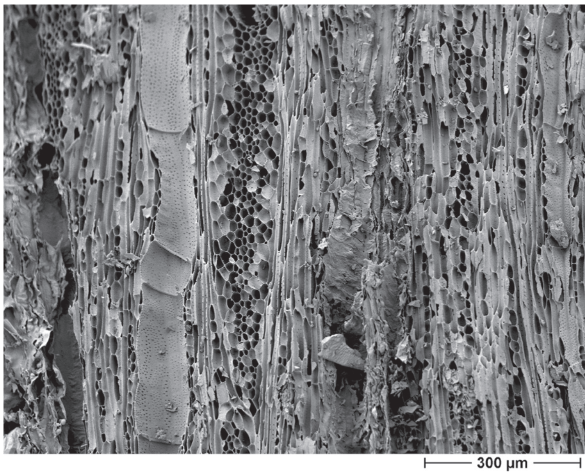

Fig. 12 *Leptadenia pyrotechnica* wood charcoal, tangential section, SEM.

being the preferred fuel used by blacksmiths in various African regions.

Other taxa are also represented in the charcoal assemblages of northern Bassar, but less common and mostly with lower percentages. Concerning the relative proportions of the dominant charcoal types, there are some distinct variations between the different slag heaps. This is particularly evident at Tchogma where *Prosopis africana* is much less represented in the slag heap 'b2', tentatively attributed to the late iron production Period 4, whereas the Sapotaceae and *Pericopsis laxiflora* are better represented than in the other heaps. A displacement of *Prosopis africana* from the local woody vegetation in the course of time might be indicated, as well as its replacement by agroforestry parkland species, particularly taxa with the ability to re-sprout vigorously after cutting. Several factors, including over-exploitation of *Prosopis africana* wood for metallurgy, might be responsible, but the expansion of cultivated areas may have also played a role. Unfortunately, it must remain uncertain whether heap 'b2' is definitely younger than the other heaps of the site, as we expected, because radiocarbon dating is not reliable for the past 300 years (Eichhorn/Robion-Brunner 2017, 162).

Meroe and Hamadab

The most striking and unequivocal evidence for the conscious and extreme selectiveness for a single species to be used as iron smelting fuel can be deduced from the results of our anthracological analyses at Meroe and Hamadab. Throughout

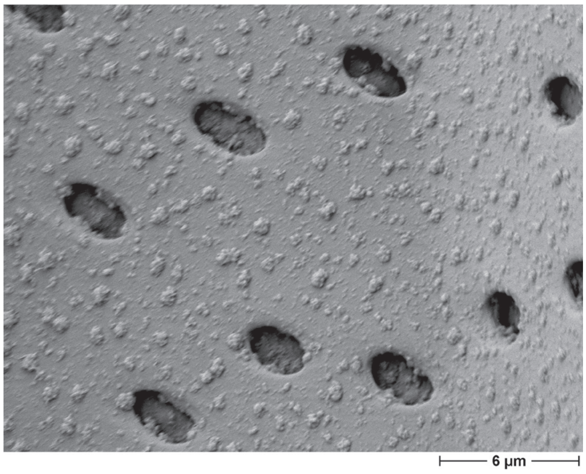

Fig. 13 *Leptadenia pyrotechnica* wood charcoal, tangential section, detail: vestured pits and vessel walls, SEM.

the entire course of the currently known metallurgical history of the Meroe region, covering more than 1 000 years, a single species, the Nile acacia *Acacia nilotica* (Syn. *Vachellia nilotica*), was predominantly used for iron smelting with values of all counted charcoal fragments ranging at Meroe from 89.9 % (Napatan and Early Meroitic periods) to 83 % (Late and post-Meroitic periods), and a value of 85 % at Late and post-Meroitic Hamadab (Humphris/Eichhorn 2019). The real relative abundances of *Acacia nilotica* charcoal fragments might even be higher because the aforementioned numbers do not include the fragments which had to be, due to insufficient preservation or vitrification, tentatively identified as *Acacia* cf. *nilotica*. The charcoal data do not point to shortage of this species as source of fuel at any point in time during the whole production period. If we assume that the fuel was sourced locally, this constant availability of *Acacia nilotica* wood charcoal certainly contradicts a dramatic over-exploitation (which *vice versa*, would have led to shortening of this particular fuel and thus to distinctly decreasing values in the charcoal assemblages). A survey of current ecology and land use in the Meroe-Hamadab region carried out by A. Malterer has revealed that the river-banks are characterised by lush woody vegetation dominated by *Acacia nilotica* and few other tree species. In this area, '*Acacia nilotica* woods' are the characteristic vegetation unit of the Nile River Valley, still extending to the Royal City of Meroe today (Wolf et al. 2014, fig. 8). In our opinion, availability was nevertheless not the only factor triggering the iron smelter's fuel choice. In contrast to the metallurgical sites, the non-metallurgical contexts at Meroe and Hamadab are characterised by a wider array of taxa used for fuel, with low values of *Acacia nilotica* type charcoal only. It is thus evident, that *Acacia nilotica* wood was in the Meroe-Hamadab region preferably used and mainly spared for the technical application of iron smelting, probably because it was considered particularly suitable for this purpose. Only few other taxa are represented in the iron smelting charcoal assemblages at Meroe and Hamadab, restricted to the late and post-Meroitic contexts. Even their choice may have been conscious, e. g. in the case of *Leptadenia pyrotechnica* at Hamadab (**fig. 11–13**) whose presence is probably related to the utility of this species as kindling (Burkill 1985, 232).

Discussion

The choice of fuel for iron smelting in ecologically different regions: similarities and differences

As described above, the three research areas differ distinctly concerning major ecological factors determining plant growth, particularly in mean annual precipitation values and the seasonality of precipitation (**fig. 6**). These factors, among many others, strongly determine the woody plant biodiversity and species composition of the vegetation surrounding the iron smelting sites, and thus the availability and distribution of taxa to be exploited for fuel. Despite these ecological differences, there are distinct similarities concerning the way woody resources were exploited in the two West African regions of Fiko and Bassar. In both areas, there is no evidence for a strong selection of one or a few single species. In contrast, a relatively wide array of taxa was used for iron smelting fuel. This diversified fuel choice corresponds well with ethnographic research conducted by J.-B. Kiethéga (Kiethéga 2009, 249 ff.), which listed a high number of species traditionally used for iron production in Burkina Faso. The same holds true for Mafa iron smelters in North Cameroon (David et al. 1989), for north-eastern Nigeria (Sassoon 1964) and for ironworking in Tanzania (Lyaya 2013). However, wood exploitation for iron smelting in Fiko and Bassar was not completely random. Oral traditions have passed on the knowledge, or at least the belief, that certain species are particularly suitable for iron smelting and were preferably used by the ancestors. These species (in the Fiko area particularly *Prosopis africana*, in Bassar *P. africana*, *Pericopsis laxiflora* and *Burkea africana*) are said to be very 'strong' or 'ardent' and to produce long-lasting heat. In two villages of the Bassar area, a mixture of the 'strong' species charcoal with a number of selected taxa, designated as 'less strong' is considered to have been advantageous. An added layer of fresh 'green' wood of selected taxa may also have left its traces in the charcoal assemblages (Eichhorn/Robion-Brunner 2017, tab. 3). Not only the oral traditions, but similarly the results of the charcoal analyses in both of the West African metallurgical centres have revealed that the choice of fuel for smelting was far from arbitrary. Although a number of taxa were identified which were not explicitly mentioned by the oral traditions (e. g. the shea butter tree, *Vitellaria paradoxa*), it is striking that only species with dense or very dense wood strongly dominate all charcoal assemblages (Eichhorn et al. 2013b, fig. 6; Eichhorn/Robion-Brunner 2017, fig. 3–4), while low-density species are almost absent. This seems to be in line with the oral tradition that 'strong' wood is required for iron smelting: It is generally considered that the calorific value of a certain wood is positively correlated with its density or specific gravity (National Academy of Sciences 1980, 24; Raven et al. 2000, 711). The National Academy judged wood density as the most important character in determining fuel quality, stating a direct correlation between the dry weight of a wood and its calorific value. According to B. J. Enquist et al. (Enquist et al. 1999) and N. G. Swenson and B. J. Enquist (Swenson/Enquist 2007), dense wood has, *per definitionem,* a higher carbon and energy content per volume unit than lighter wood. Actual measurements of wood densities in relation to calorific values show, however, a less unequivocal correlation, indicating that a lot of basic research is still required to fully understand the factors triggering the fuel quality of a woody species. B. Klašnja et al. (Klašnja et al. 2013) found higher calorific values for the dense wood of black locust compared to the lower-density woods of willow and poplar species, whereas W. Hubau et al. (Hubau et al. 2014), when studying 15 tropical African rainforest taxa, did not find a positive correlation between their wood densities and calorific values. F. Munalula and M. Meincken (Munalula/Meincken 2009, fig. 1), in turn, provided clear evidence for the direct correlation of average wood density and the calorific values of five South African fuel wood species, yet the calorific values of the different species varied only in a narrow range. According to B. L. Corradi Pereira et al. (Corradi Pereira et al. 2012) the use of very dense wood for charcoal production results in an elevated production of charcoal for a certain volume of wood and the charcoal quality is improved for various purposes, such as the production of pig iron and steel.

If we now consider the highly selective fuel choice at Meroe and Hamadab (hereafter referred to as the Meroe area), it is evident that a high-density wood was also chosen in this case. The calorific value of *Acacia nilotica* wood is likewise very high (National Academy of Sciences 1980, 98; Carsan et al. 2012). Fuel quality thus seems to have been a decisive factor for the selection of *Acacia nilotica*. The almost complete restriction to a single taxon for iron production fuel is, in spite of this, absolutely exceptional among our three case studies. In addition to fuel quality, other factors must therefore be taken into consideration. The differences in the natural ecological conditions and land use practices between the West African sites and the Meroe area certainly also played an important role. The species composition of the northern Bassar and Fiko tradition sites indicates that the diverse, mosaic-like zonal vegetation surrounding the sites (agroforestry parks with fields and fallows, savannas) was the primary source of iron smelting fuelwood. West African savannas are highly reproductive systems and even fields and fallows in traditional agroforestry systems may reproduce a considerable amount of wood (Clément 1982; Ohler 1985; Breman/Kessler 1995; Nouvellet et al. 2003). In contrast, the arid matrix around the Meroe area is a zonal semi-desert vegetation, characterised by low net primary productivity (Clément 1982; Ohler 1985; Breman/Kessler 1995; Nouvellet et al. 2003). But extrazonally, lush *Acacia nilotica* woods are the vegetation unit of the Nile River Valley (Wolf et al. 2014, fig. 8). We can certainly state that these were the primary source of fuel for the iron metallurgy. From the early 1st millennium BC, the environments of the Meroe area, with the geomorphology of its floodplain and its seasonal streams, were particularly favourable compared to other locations further north which had become harsh environments due to increasing aridification and decreasing Nile levels (Wolf 2015, 130). Over fifty years ago, A. J. Arkell (Arkell 1961, 147) postulated that Meroe was a particularly favourable location for iron production due to its iron ore *and* its wood resources.

The 'hidden agenda': human plant interactions beyond iron smelting, and the possible role of cultural factors

In our previous publication (Humphris/Eichhorn 2019), we described further factors of human-plant interactions which may have promoted *Acacia nilotica* in the Meroe area: 1. Its ability to cope with coppicing, a wood management system involving the felling of trees to almost ground level, from where they regenerate. *Acacia nilotica* withstands coppicing as well as pollarding (National Academy of Sciences 1980, 98; Gessesse et al. 2015); 2. the value of this tree for multiple purposes, first of all as an ancient source of gum arabic, but also as a valuable source of tannin for tanning leather, as medicine, fodder, decoration (flower garlands), as source of honey and other uses (National Academy of Sciences 1980, 98; Gerisch 2004, 99). It was therefore not only the production of high quality charcoal that could have encouraged the people of the region to manage the stocks of this species, but also the high economic value of the tree in general.

From a technological point of view, other woody taxa and mixtures of woody taxa are also well-suited for iron smelting, as indicated by our studies in West Africa and as can be deduced from information from other metallurgical traditions in Africa, where wide arrays of species were exploited for fuel as mentioned above. While high burning quality in combination with availability, possibly maintained by management and/or import along the Nile, are striking arguments for the dominant selection of *Acacia nilotica* by the iron producers of Meroe and Hamadab, there are other less obvious but imaginable reasons determining highly selective fuel choice. Conservative behavioural patterns, religious restraints and belief systems may have played an important role, although such factors are so far unidentifiable in the archaeometallurgical record of the Meroe area (Humphris/Eichhorn 2019). Traditions of wood selection may have developed and continued because the smelters simply *believed* that the Nile acacia was the only fuel allowing for successful iron production – comparable to the West African smelters and their inheritors who *believed*, and many still do so, that some woody species are particularly 'strong' and/or 'ardent'. The preferred choice of hard-wooded species has been reported by G. Celis (Celis 1991, 23 ff.) for several African regions. According to G. Celis, the smelters stated that these species were indispensable for successful smelts. Despite this belief, G. Celis did not observe negative consequences where the traditional fuel was substituted by other, introduced species, and concluded that the smelters' statements were driven rather by their inherited duty to follow strong traditions than by comprehensible technological reasons.

Assessing the environmental impact of ancient sub-Saharan iron smelting: is it feasible?

Wood is a renewable resource and its exploitation for fuel can be sustainable as long as the harvested amount in a given time and space does not exceed the respective regrowth (e. g. von Maltitz/Scholes 1995, 243; Twine/Holdo 2016; Swemmer et al. 2019). In order to evaluate if wood use at the three African iron metallurgy centres was sustainable or unsustainable, both factors, consumption and reproduction, have to be taken into consideration. It is furthermore necessary to delineate the spatial extent where wood was potentially harvested, and a reliable time frame for fuel use and woody biomass reproduction. Wood consumption values can only be deduced via conversion factors from measurable values such as slag volume and mass which can be achieved through the archaeological excavations. In the case of the Fiko sites, the time frame could be assessed through numerous radiocarbon dates obtained from charcoal fragments from the excavated slag heaps supplemented by information from oral traditions. Directly quantifiable factors available to us were the amount of metallurgical waste, represented by the volume of the slag heaps and the spatial extension of the Fiko tradition. In a model approach, not respecting spatial variations within the area, we thus tried to quantify mean annual slag output of the Fiko tradition and to derive annual wood use and annual wood reproduction for the entire area where the Fiko tradition sites were distributed. It is generally considered that the fuel predominantly used for West African bloomery was wood charcoal, although rare exceptions involving the use of dry uncharred wood have been recorded during ethnohistorical surveys (Djerma/Niger, Fouta Djalon; Celis 1991, 24). In order to quantify the woody biomass used, we therefore had to establish conversion rates between, firstly, fresh wood with high moisture content as it prevails in the vegetation; secondly, dry wood at the beginning of the charring process and thirdly, the charcoal itself. Subsequently, the amount of slag produced and charcoal employed during slag formation had to be related. Data on woody biomass reproduction had to be drawn from ecological literature.

J. Clément's seminal study (Clément 1982) related the productivity of West African mixed wood grass formations to annual precipitation and site characteristics such as soil quality and human impact, revealing a generally strict relationship between annual rainfall and wood productivity. J. Clément subsequently developed three productivity curves: one for sites protected from fire and other severe anthropogenic impact (i max), one for unprotected sites and medium soil quality (i 0) and one for degraded sites on poor soils (i min). For the period in question, we presumed an established agricultural system with a large area under cultivation or fallow. Shallow soils on acid sandstone surfaces covering a high percentage of the research area were considered as slightly productive, whereas the gallery forest of the Yamé River was regarded as more productive due to its high water balance. Overall productivity for the area must thus have most probably been somewhere between the values for i 0 and i min. An estimated mean basic density of 650 kg/m^3 compiled from ecological literature was subsequently used in our calculations in order to convert wood volume into mass. In the case of the Fiko tradition sites it led us to the assumption that wood use for iron smelting in this particular area must have taken place below but close to the ecological threshold (detailed description and further references in Eichhorn et al. 2013b, 61 ff.). Fuel for iron smelting is only one of numerous traditional (West) African wood consuming activities. Fuel for refining the bloom, for subsequently shaping the raw material into useable objects (although as the Fiko tradition produced surplus iron, it may be suggested the production of finished items possibly took place elsewhere), for ceramic production, cooking, and construction would have to be added in order to achieve realistic total wood consumption data. The Fiko tradition demonstrates that despite a well-established chronology, such a model approach has a number of pitfalls, particularly due to the high number of variables included in the calculation, but also due to the fact that this approach does not take possible periods of higher production and thus elevated wood exploitation into account. For example, one of the variables which may include errors of a certain magnitude is the initial measurement of the metallurgical waste volume as part of the former slag may have been repurposed for building and road construction in the past (Iles 2016, 1227). Though often simply designated as slag heaps, metallurgical waste is in reality quite heterogeneous, consisting of slag, tuyère and furnace wall fragments, charcoal remains and sediment (Humphris/Carey 2016). Furthermore, this value may vary within a waste heap, in between waste heaps of a single working sector, and between the working sectors of a metallurgical site. In order to achieve realistic values of slag mass, systematic slag mass per volume measurement using the 'cubing' technique are necessary (Robion-Brunner/Serneels 2017). All in all, our applied model approach can only provide a rough order of estimate of wood consumption for iron smelting. The anthracological studies in the Fiko tradition area have, furthermore, provided evidence for an uneven impact of iron-smelting on the local scale. At Fiko, where iron production was practiced continuously in a small region in the area around the village of the same name, distinct changes concerning species composition and abundance occurred in the course of time. In Kéma however, the repeated displacement of the metallurgical sites scattered the impact on the woody vegetation.

In Bassar, our initial working hypothesis was that the woody vegetation of the area should be more resilient than the Fiko tradition area towards wood-cutting because, due to much higher mean annual precipitation values, a higher woody biomass reproductive capacity may be expected. Our analyses concentrated on the two site complexes of Tchogma and Tatré together covering the periods of iron production Periods 1 to 4 according to P. De Barros (De Barros 1986). The results of the anthracological analysis seem to indicate that already during Period 1 an agroforestry system was well-established. The frequent occurrence of taxa with the ability to re-sprout after cutting points to a strong regenerative capacity of the woody vegetation. The interpretation at Tchogma where distinct variations in the anthracological assemblages are visible, pointing to the decrease of *Prosopis africana* and the *Terminalia* species and an increase of the agroforestry tree shea butter *Vitellaria paradoxa* and the vigorously re-sprouting *Pericopsis laxiflora* is to a certain extent hampered by insecure radiocarbon dating for the past 300 years.

At Tatré, the general image is similar, with the exception of an increase of *Prosopis africana* in the presumably most recent investigated slag heap close to furnace 33, attributed to Period 4. Whether this might be related to provision during this late period with charcoal from a charcoal production site elsewhere (such as Dimuri, where in memorable times charcoal was produced to be sold at the market of Bandjeli) has to remain speculative, but might offer a convenient explanation. While the attempt to extrapolate the model calculations developed in Fiko to the entire Bassar area has pointed to sustainable wood exploitation below the ecological threshold (Eichhorn et al. 2013b; Eichhorn/Robion-Brunner 2017; Garnier et al. 2018), this general approach is unsuited to test the impact on a more local scale e. g. at Tchogma or Tatré, where intensive production in a small area took place. At Tatré, this problem could partly be met by sedimentological and phytolith analyses in the Tatré River valley which are complementary to the wood charcoal analyses (Garnier et al. 2018). Contemporaneous with intensive iron smelting, as evidenced by radiocarbon dating and embedded slag fragments, there are distinct changes in the sedimentary record indicating the impact of metallurgy at a local scale. Vegetation degradation or soil erosion increased the sensibility of the river's catchment area to erosion during that period. The phytolith assemblages indicate a weak but significant reduction of the tree layer in favour of grasses, and thus increasing openness of the vegetation. Furthermore, among the phytolith morphotypes that represent the tree and shrub layer (woody dicotyledon phytoliths), globular decorated phytoliths are reduced in favour of sclereids, indicating changes in woody species composition or relative abundances similar to the anthracological results pointing towards an increasing importance of taxa able to re-sprout. However, the combination of the anthracological and the phytolith data suggests, all in all, a suitable management of the tree layer. Furthermore, the results underline that the direct impact through vegetation degradation is not the only one to consider. The generalisation of iron tools certainly contributed to improve and diversify agricultural practices. Increasing cultivated areas and changes in soil cultivation practices may have locally strongly impacted the landscapes and the hydro-sedimentary dynamics.

L. Iles et al. (Iles et al. 2018) come to akin conclusions in North Pare (Tanzania) where erosion processes were already well established before the documented intensification of smelting and smithing activities. They suggest, that although iron production may well have contributed to deforestation and erosion at Pare, it is unlikely to be the sole causal factor.

In the Sahel and the Northern Sudanian zone of West Africa, agricultural intensification in concert with cattle herding distinctly modified the vegetation composition particularly during the Late Iron Age, a development which was certainly still enhanced by the direct consequences of wood cutting for metallurgy and fuel in general (Höhn/Neumann 2012; Eichhorn/Neumann 2014, 91 f.).

Establishing a firm chronology of an area's iron smelting history allowing for the assessment of annual slag output, which serves, among other factors, as the reference for wood consumption, may be a complex and tricky task. For Meroe and Hamadab, J. Humphris and T. Scheibner (Humphris/Scheibner 2017) have described the factors potentially having influenced the original formation of the slag mounds:

1. The stratigraphic sequence in a trench section does not inevitably reflect the absolute chronological order of metallurgical waste production or of mound formation. In the course of building up the heap, older material may have been deposited over younger material, for example if waste from earlier metallurgical activities was moved.

2. The original handling of iron production waste is almost impossible to reconstruct. As an example iron production spaces and workshops may have been regularly cleaned and the waste carried to the slag mound immediately, or the waste may have been kept in the workshop's vicinity until a certain amount of waste was produced, before it was finally deposited on the mound. This implies that asynchronous material may be embedded in the stratigraphy, which is then erroneously assumed to represent a consistent chronology.

3. The slag mounds display a complex horizontal stratigraphy due to the formation process, which cannot be understood before excavation. Hence the positioning of the excavation trenches may not be pre-adjusted in a way that would ensure the most meaningful sampling opportunities for dating samples.

4. Although individual trench stratigraphy may be well-defined, stratigraphic relationships between distant trenches remain elusive.

In addition to the uncertainties concerning the wood consumption represented at Meroe and Hamadab (in addition to the fact that most of the archaeometallurgical remains at Meroe are yet to be investigated), which are still enhanced by the possibility that wood was not only sourced locally, but possibly partly provided by transport via the Nile River, it is also difficult to estimate the annual re-growth of woody biomass in this region. The Nile and its floods are less dependent on local precipitation values than on those in its vast catchment area. This also influences the plant water availability in its flood plain and gallery forests, decisively effecting woody biomass reproduction. Evaluating wood consumption and reproduction in this area is thus a matter of ongoing research that must be systematically adapted to historical and environmental contexts.

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Acknowledgements

The anthracological and archaeological research in the Fiko area (Mali) was funded by the Deutsche Forschungsgemeinschaft in the frame of the projects 'Holocene vegetation history of Ounjougou' and the DFG-ANR project 'APPD: Landscape Archaeology in the Dogon Country' and by the Swiss National Science Foundation (FNS). Research in the Bassar area (Togo) was funded by the Agence Nationale de Recherche in the frame of the programme ANR/JC SIDERENT 'Siderurgie et Environnement au Togo: Stratégies d'exploitation des ressources naturelles dans le cadre d'une production du fer ancienne et intensive (region bassar, Togo), ANR-13-JSH3-0002-01.

UCL Qatar and QSAP (the Qatar Sudan Archaeology Project; grant number 037) have provided funding for the archaeological research in the Meroe and Hamadab region (Sudan) while the British Institute in Eastern Africa funded the anthracological investigations.

Dr Pawel Wolf and Dr Hans-Ulrich Onasch are thanked for providing charcoal samples for additional study. Particular thanks are due to Prof Katharina Neumann, Prof Vincent Serneels, Dr Philip De Barros and Prof Eric Huysecom for their support. We wish to thank Manfred Ruppel for taking the SEM photos.

Image reference

Fig. 1, 7–9 B. Eichhorn.
Fig. 2 Illustration: B. Eichhorn/Map basis: Rivas-Martinez et al. 2010, modified.
Fig. 3–5 C. Robion-Brunner.
Fig. 6 B. Eichhorn/J. Humphris/C. Robion-Brunner/A. Garnier.
Fig. 10 J. Humphris.
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