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The role of metallurgy in transforming global forests.

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Abstract
Forest degradation – both past and present – has become a significant research focus of many disciplines in recent decades, and it is an area in which the multidisciplinarity and long-term perspectives of archaeological endeavor has the potential to make a particularly valuable contribution. One of the past craft activities that has long been linked to significant socio-economic change and associated accelerations in forest cover reduction and environmental decline is the intensification of early iron production – an industry reliant on the consumption of charcoal as fuel for much of its history. However, the impact of iron production on the transformation of woodlands is dependent on a suite of interrelated factors – climatic, ecological, technological and cultural – only some of which have so far been adequately scrutinised.

This paper explores the theoretical context that links iron production with deforestation in academic and popular cultures, examining the role that archaeology can play in investigating this association, before reviewing recent methodological approaches that aim to interrogate the relationship between metallurgy and the environment in archaeological settings.

Iron; metallurgy; environment; deforestation; charcoal; technology

Introduction

Human-environment interactions in the context of iron production

Many of the most vigorous socio-economic debates of today concern the relationship between human populations, climate and the environment[1]. We seek not only to understand how people impact upon their environments – on local, regional and global scales – but also to assess how populations respond and adapt to environmental and climatic shifts (e.g. Adger et al. 2012). A core aim of these analyses is to anticipate and manage future environmental changes, and one way in which this can be pursued is through close examination of human-environment interactions in the past alongside an interrogation of their short- and long-term consequences. Archaeology – with its focus on teasing apart the complexities of natural and social processes over the *longue durée*, as well as its integrated use of sources and its multidisciplinarity – should be well placed to contribute to these debates, not least by breaking down the culturally-constructed assumptions on which environmental arguments are often based (Kirch 2005; Davies and M'Mbogori 2013). In recent years, and with increasing degrees of scientific rigour, archaeological data have successfully been used to tackle large-scale, timely and relevant questions of global environmental change (cf. Kirch 2005; Ellis 2015), ranging from the contribution of agriculture, deforestation and pastoralism to early methane levels (Ruddiman 2003, 2005; Fuller et al. 2011), to the link between patterns of early land clearance and global carbon emissions (Kaplan et al. 2011). These examples have served to demonstrate the potential of archaeological methods and data to contribute to a fuller understanding of the dynamics of regional and global environmental change, and importantly, the role of human populations and social agency in these changes. However, in general archaeology has struggled to communicate its findings to non-archaeological audiences (Mitchell 2008), leaving scholars in other disciplines to rely on outdated or disputed data when looking at long-term anthropogenic contributions to environmental change[2].

Deforestation has been a particular and ongoing concern to ecologists, not only in terms of conservation of biodiversity, but also because of the established relationship between deforestation and changes in global climate (Lawrence and Vandecar 2015). Assessing

[1] For evidence of this, look no further than the heated exchanges between Matt Ridley and other commentators in the Wall Street Journal (Ridley 2014a, b, c, 2015; and responses in Partridge et al. 2014; Sachs 2014; Hansen et al. 2015).

[2] Compare Bayon et al. 2012a with responses (Maley et al. 2012, Neumann et al. 2012, Bayon et al. 2012b); and Maina et al. 2013 with Kull 2000.

the extent (e.g. Miettinen et al. 2014) and impact (e.g. Aber et al. 2001; Hosonuma et al. 2012; Thompson et al. 2013) of forest degradation and deforestation have thus become research priorities of many disciplines, and it is one arena in which archaeology has an opportunity to make a valuable contribution (Williams 2000; e.g. Kaplan et al. 2009). Several human factors are known to influence deforestation processes, including – but not limited to – agriculture, conflict, population increase and charcoal production (Bamba et al. 2011), all of which are long-standing archaeological preoccupations. Of interest in this paper is charcoal production – a core component of traditional metal production processes, as well as many other industrial and domestic activities. The high volume of charcoal required to smelt metals from ores has meant that for centuries, the development and intensification of metal production has been linked to reductions in forest cover, environmental decline and associated socio-economic change:

"…the woods and groves are cut down, for there is need of an endless amount of wood for timbers, machines, and the smelting of metals. And when the woods and groves are felled, then are exterminated the beasts and birds [...] Therefore the inhabitants of these regions, on account of the devastation of their fields, woods, groves, brooks and rivers, find great difficulty in procuring the necessaries of life..."

Agricola 1556 [Hoover and Hoover 1950: 8]

Echoing Agricola's observations of sixteenth century Bohemia, the degrading impact of metal production industries on local and regional forest environments has more recently been invoked in archaeological research contexts around the globe (e.g. Muntz 1960; Voss 1988; Okafor 1993; Haaland 1980, 1985; Bayon et al. 2012a; Lupo et al. 2015). However, a methodical and rigorous demonstration of the triggers of environmental degradation is often not attempted in these cases (Wagner 2013), with instead a heavy burden of proof placed on observed correlations between archaeological evidence for industrial activity and palaeoenvironmental proxies for environmental decline. Given the rising interest in global causes of deforestation, a recent suite of archaeological research has now begun to systematically address the complex relationship between iron production and environmental change, drawing upon archaeometallurgical, archaeobotanical and geoarchaeological datasets to investigate metal production's role in changing vegetation patterns.

This paper considers why iron production is so readily and often unquestioningly linked with deforestation in academic and popular cultures, before reviewing recent archaeological approaches to examining the proposed link between iron metallurgy and the environment. In doing so, important developments and obstacles encountered in the pursuit of understanding this relationship will be highlighted, in the hope that this scrutiny and reflection will inform future research design – both archaeological and non-archaeological – on this increasingly important topic.

There's no iron without fire[3]

The premise of the relationship between iron production and forest degradation appears, on the surface, to be simple. Charcoal is a fundamental component of bloomery (or solid-state) smelting to extract iron from an ore, and it was also used as fuel in earlier examples of blast furnaces and fineries. In the UK, it was not until the development of coke-fuelled blast furnaces in the eighteenth century that the iron industry was freed "from dependence on the speed at which trees grew" (King 2005: 24); in the USA, the reliance on charcoal continued until the late nineteenth century, when up to 75 per cent of iron was still produced using charcoal as fuel (Mosley 2010: 33; see also Muntz 1960). Fuel, whether in the form of wood or charcoal, may also be required at several further stages of the iron production process depending on the technology being undertaken, which might include fire-setting to extract ores, roasting or pre-treating ores prior to smelting, or refining of pig iron (to remove excess carbon and other unwanted elements). Finally, the smithing process itself – in which iron is shaped into useable objects – also demands fuel for the hearth (Crew 1991; Humphris 2010).

Thus, on the most literal level, it can assuredly be stated that bloomery production of iron necessitates the consumption of tree mass. Following the principles encapsulated in the IPAT equation[4], it would also seem logical to suggest that growth in iron production activity would consume ever-increasing areas of woodland, ultimately resulting in deforestation. The forest resources targeted by iron producers are routinely thought to be "constantly under increased pressure", due to technological innovations and ever-growing demand driving forward production rates (cf. Ludemann 2010; Arribet-Deroin 2013: 454). However, as shall be discussed, the subtleties of the iron/environment relationship – as with the IPAT equation – have been found in recent decades to be more complex than previously thought, governed not just by the volume of charcoal required by a given iron production industry, but also by the nature of socio-economic and

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[3] Excepting naturally-occurring, yet rare, telluric and meteoritic iron.

[4] IPAT proposes the simplistic equation that impact (I) is the product of population (P), affluence (A) and technology (T) (cf. Chertow 2000; Lambin et al. 2001).

ecological interactions with forest resources. Iron production doesn't simply require charcoal, it requires a *supply* of charcoal in harmony with the charcoal demands of other production and household activities if it is to operate as a viable ongoing industry. The annual consumption of fuel is an obvious marker of resource use, but how that requirement is distributed throughout the year, and what forest resources are collected (such as preferences for specific species, cf. Mapunda 2003; Lyaya 2013) will determine its overall impact. Other demands on fuel resources such as day-to-day domestic activities (e.g. building, cooking) and other pyrotechnologies (e.g. ceramic and lime production), as well as landscape changes due to burning or clearing for agriculture and/or grazing, or for defence (Hughes and Thirgood 1982; Rollefson and Köhler-Rollefson 1992; Mighall and Chambers 1997) also play a significant role. The relationship between iron production and wood resources is heavily dependent on these additional factors as well as the scale of an iron industry, the structure of forest resources and the management of local woodlands.

The intensity and organisation of production contributes significantly to the impact of an industry on a given forest. Local management strategies, such as spatial, temporal or social restrictions on harvesting plant resources, practises of coppicing or pollarding, and the protection of sapling trees from browsing animals (Coffin 1880; Hart 1971; Evans 1984), make a great difference to the sustainability of a resource over time, and yet are influenced by complex socio-economic factors. At one extreme there is temporary industrial production based around rapid overexploitation of local resources, which results in resource depletion and industrial decline or relocation. At the opposite end of the spectrum lies a scenario whereby low intensity production and/or active resource management ensures a continued supply of fuel, enabling long-term, sustained iron production. By employing suitable management strategies, under 2 per cent of the land surface of England and Wales "could have sustained the maximum output of the British charcoal industry for ever" (Hammersley 1973: 606), and the *Journal of the United States Association of Charcoal Iron Workers* reported that "we are really the only trade organization whose interest it is to encourage the growth of forests" (Coffin 1880: 33). However, even the recent historical record indicates that the implementation of good management strategies is at best variable (Muntz 1960; Hart 1971).

The regenerative capacity of woodland is a critical factor in assessing the impact of a past industry: woodland composed predominantly of fast-growing species will be more resilient to intensive use than those dominated by slower-growth trees. Nevertheless, independent factors such as climate, disease or fauna might help or hinder forest resilience and recovery at a particular time. Forests are not static entities, and they naturally transition between growth cycles of different types of species and forest structures, resulting in natural shifts in forest composition and biodiversity. External stressors such as climate or fire play pertinent roles in maintaining or changing these compositions, although the capacity of forests to withstand even significant climatic variation is noteworthy (Thompson et al. 2013). This natural variability complicates efforts to evaluate the decline or degradation of a forest at a given point in time; establishing a baseline against which the forest can be measured over the long term must account for these natural variations. Today, forests are assessed in terms of a variety of characteristics and functions, including biological diversity, vitality, productivity, protective functions and socio-economic roles (Miettinen et al. 2014) – a highly complicated range of attributes that would struggle to be assessed in a historical setting.

The balance between these two primary elements – the draw on forest resources and the rate at which resources regenerate – are central to the issue of metallurgy's relationship with the environment. Gaining a thorough understanding of these factors, how they interact with each other and how they change through time, is necessary in order to build a picture of industrial impact on the environment. The dynamic interdependence of numerous influences is the biggest challenge faced in understanding changes in the past environment. It is significantly more difficult to understand these factors in the past in view of the fact that archaeological and palaeoecological datasets are often incomplete: these datasets depend on suitable sedimentation and preservation conditions that allow for a comprehensive reconstruction of past cultural activity and ecology through time. Even ecologists tend to evade this complication by discussing changes in vegetation based on short-term vegetation data extrapolated to the long term, rather than historical information (Fairhead and Leach 1996: 55), emphasising the extent of the challenge encountered by archaeologists in this field.

Background

Discourses of environmental change

Narratives of environmental change in the media and popular culture are often highly simplified and have a tendency to be pessimistic, with a prevalence of unicausal perspectives and a persistent focus on extreme environmental or social collapse (e.g.

Diamond 2005). Unfortunately, these reductive narratives can eventually become established as received wisdom, accepted without challenge (Lambin et al. 2001; Lane 2009) – a pertinent issue when considering attitudes to the relationship between environmental change and industrial intensification over time. In contrast to the media's "sensationalist, catastrophic bias" (Smil 1993: 1), notions of simple 'cause and effect' have in recent years been challenged in ecological research, and the complex dynamics of environmental systems and culture-environment interactions have begun to be prioritised, renewing calls for the integration of socio-cultural processes alongside biological processes when examining ecological change (Ellis 2015).

As anthropologists, archaeologists and historians have in the last few decades developed new approaches to deal with increasingly recognised variations in social complexity, so ecological theorists have become aware of "disorganisation and complexity in natural processes" (Sivaramakrishnan 1999: 14). The binary position of land-use (aka degradation) versus nature (aka equilibrium) has been rejected. Simplistic notions of pristine landscapes and environmental balance misinform the ways in which changing environments are understood and problematised (Beinart and Coates 1995; Lambin et al. 2001; Beinart and McGregor 2003: 2; Fairhead 2013: 259), and it is increasingly clear that change is as normal as stability in socio-ecological systems (Redman 2012: 237). It is now recognised that landscapes previously thought of as pristine may have had a much more complex history of human-environment interactions (Fairhead and Leach 1996; van Gennerden et al. 2003; Erickson 2006; Brncic et al. 2007; Balée 2013; Fairhead 2013). Forests are seen less as ancient, unspoilt ecosystems (e.g. Brncic et al. 2007; Vlam et al. 2014) and more as dynamic changing landscapes, with consequences for how the relationship between iron metallurgy and woodlands is conceptualised and addressed.

Historical legacy: paradise lost?

"In spite of the lack of conclusive evidence for deforestation, it undoubtedly occurred, given the large quantities of wood required as construction material and fuel for ceramic production as well as household consumption".

(McClung de Tapia 2012: 149)

"In the contemporary wisdom, degradation is assumed unless the opposite is demonstrated".

(Butzer and Harris 2007: 1933)

The two quotations above demonstrate that there is still a tendency in archaeology to present a diagnosis of landscape degradation even when positive evidence for it is lacking or absent. Popular rhetoric is inclined to invoke nostalgia for a once-pristine ancient landscape that has since been subjected to gradual but relentless decimation by human populations: a paradise lost (see discussions of this mythology in Ingold 2000; Kirch 2005; Davies and M'Mbogori 2013; Ellis et al. 2013). Industry is often seen as the culprit. Indeed, as we have seen, concerns about the link between industrial-scale production of metal and the destruction of forests are centuries, if not millennia old, stretching back to the writings of Theophrastus and Herodotus in the first millennium BC (cf. Hughes 1983), and reinforced by representations of the intensification of industry in literature and art (see, for example, Philip J. de Loutherbourg's apocalyptic 'Coalbrookdale by Night', painted in 1801, at which point Britain was among the "least wooded countries in the European forest zone" (Hammersley 1973: 593)).

Certainly, the development of heavy industries in Europe did have profound effects both on society (e.g. Evans 2014) and on local environments, causing air pollution, water pollution and the leaching of heavy metals into the soil (Marshall 2003 and references therein; Mighall et al. 2009; Williams 2009; Boyle et al. 2015; Cooke and Bindler 2015; Karlsson et al. 2015). However, historical accounts that 'read the landscape' are inherently subjective; the environment is not an objective phenomenon, rather, all perceptions of the environment and of environmental change are shaped by social or cultural expectations and memories (e.g. Davies 2013: 6). Rackham illustrates what he terms the 'pseudo-history' effect with the example of iron production in the The Weald, Sussex (Rackham 2000). He presents two seemingly contradictory accounts of the condition of local woodlands, written sixty years apart. The earliest, written in 1664 by John Evelyn, argues that iron and glass production ransacked The Weald's woodlands. Just over half a century later, Daniel Defoe counters that the woods remained a viable resource despite the demands made on them by the extensive iron foundries. Rackham attributes these seemingly contradictory first-hand accounts to the subtle subjectivities of the authors. With the benefit of comprehensive land-use surveys, maps, geoarchaeological and ecological data, Rackham proposes that the woods had in fact been broken up by medieval agricultural systems long before Evelyn's account was written, and that the foundries utilised underwood and coppiced wood from renewable, managed sources. Indeed, The Weald has the most heavily concentrated area of ancient woodland in the UK today (Westaway 2006). It is the *change* in forest availability rather than its destruction that may have influenced Evelyn's perception. The coppiced woodlands desirable for iron working may have become unusable for timber production, and may have appeared to be destroyed when newly cut, even though regrowth would have occurred. Alternative factors now known to have contributed to the decline in Wealden iron include failing water supplies, the relatively low grade of iron ore and high operational costs (Hammersley 1973). Has iron production been blamed unfairly for environmental degradation and landscape change in other periods and regions?[5]

The notion of the destruction of a previously 'pristine' landscape has without doubt been transported elsewhere in the world. Colonial accounts of African and Indian landscapes described retreating forests and dramatic soil erosion, believed to be caused by unbridled population growth and irresponsible forest clearance by disinterested local farmers (Sivaramakrishnan 1999: 3). Blame was often placed on these indigenous populations because of notions of their perceived ignorance, their "intellectual incapacity for reflection" and their pre-occupation with short-term gains (Fairhead and Leach 1996: 29). The expertise and knowledge of those who worked in the forests was overlooked (Hughes and Thirgood 1982: 62). However, it is the colonisers – with little understanding of local environments – rather than local populations, who are likely to have instigated the most damaging environmental changes. A European forester working in Bengal in the 1920s perceptively declared, "we talk glibly about following nature and forget that the nature we are visualising may be a European nature inherited from our training and not an Indian nature" (in Sivaramakrishnan 1999: 232). In seeking to exploit the land for cash crops using European farming methodologies, and by implementing European forest management strategies to maximise timber extraction, the structure of local landscapes was altered, local knowledge was undermined and the relationship between local communities and their environments was ultimately distorted (Beinart 2000; Tilley 2003). In the early twentieth century, smelters in India and Africa suddenly found themselves in competition with colonial administrations for forest resources (cf. Sivramkrishna and Jyotishi 2015). In some places iron and charcoal production were forbidden entirely with the explicit intention of protecting forests (e.g. de Barros 1986; Killick 1990), which concealed – some suggest – a hidden agenda of suppressing local iron production in order to support the iron

[5] In a similar fashion, blacksmiths of medieval London – who couldn't help but draw attention to themselves with noisy and smoky workshops – shouldered much of the blame for increasing air pollution throughout the thirteenth century, now attributed to rising levels of lime production in the city (Brimblecombe 1987).

industries of European nations, whether at home or abroad (e.g. Sivramkrishna and Jyotishi 2015; although see discussion in Evans 2015).

Metallurgy and deforestation thus became fundamentally intertwined, importantly just at the point at which archaeology was becoming established as a discipline in its own right. Moreover, opinions of how these 'primitive' peoples in colonised territories interacted with their environments fed directly into budding hypotheses of the relationship between past societies and their environments in broader archaeological theory.

Developing approaches and managing challenges

In order to address the relationship between iron production and landscape change it is necessary to bring together multiple lines of cultural and ecological evidence. Unfortunately in archaeological investigations it is rare for all the desired evidence to be obtained at a single site: more often than not, datasets are limited by their availability[6]. Nevertheless, with changing theoretical frameworks and developments in data collection strategies, the subject has been tackled with shifting emphases on different strands of archaeological evidence over the past few decades.

Early strategies

From the late 1970s, archaeological research explicitly addressing deforestation and metallurgy began to emerge, at around the same time that archaeological science and environmental archaeology – as part of the New Archaeology – were becoming firmly established as archaeological sub-disciplines. Ecosystems were newly placed "at the heart of archaeological explanation" (Davies 2013: 15), also influencing archaeometallurgical research. Over the next couple of decades, the body of literature exploring the link between metallurgy and landscape change expanded dramatically. However, these pioneering studies tended to have an archaeometallurgical rather than an archaeobotanical emphasis (e.g. Cleere 1974; van der Merwe and Killick 1979), and they focused almost exclusively on quantifying charcoal consumption in relation to estimated metal output. The most frequent methodological approach comprised a calculation of the volume of charcoal required to produce the slag at a given site, an

[6] Even historical records of the more recent iron industries in the UK and elsewhere struggle to build a comprehensive and precise account of all inputs and outputs of furnace works (e.g. Hart 1971; Hammersley 1973; Ryzewski 2013), particularly in early historical periods.

approach formulated from a metallurgical, or at least, technological viewpoint. The outputs of these early papers were approximate (but often dramatic) estimates of the woodland acreage needed to support the smelting output of a given site (e.g. Cleere 1974; van der Merwe and Killick 1979; Haaland 1980, 1985; Goucher 1981), and although they placed little weight on archaeobotanical data, they set the scene for the development of quantitative perspectives on the environmental impacts of metallurgy across the globe.

Much of this early research was based in sub-Saharan Africa (e.g. Haaland 1980, 1985; Goucher 1981; van der Merwe and Killick 1979; Okafor 1989; Schmidt 1989), a region rich in ethnographic information detailing contemporary fuel use preferences and fuel collection strategies – a source of data that also resonated strongly with the ideals of the New Archaeology. This seemed to be an excellent setting in which to understand the resource demands of past smelting activity, producing data that could be extrapolated to understand the impact on past environments. Typical was Haaland's (1980, 1985) research examining Sahelian iron metallurgy. Drawing together an ethnographic study of iron production in Darfur, Sudan (Haaland 1980) with estimates of the volume of metallurgical waste at large scale iron production sites at Mema in Mali and Meroë in Sudan, Haaland calculated the volume of charcoal – and thus the rate of felling trees – required to support these past industries. She concluded that iron production on such a scale would have exceeded forest regeneration rates, prompting deforestation.

In many instances, the volume of wood needed for these industries is thought to have been vast, and interpretations generally judged that iron production would have had an overwhelmingly negative impact on local environments: Goucher (1981) estimated that 300,000 trees would have been needed over the lifetime of the iron production site of Dapaa in Ghana; Haaland (1980, 1985) suggested that 480,000 m^3 of wood were needed to make charcoal in Mema over the course of 300 years and 450,000 m^3 at Meroë over 350 years. However, calculations such as these – which often form the basis of assessments of landscape degradation – are not straightforward. They are reliant on a number of estimations at each level of analysis, drawn from ethnographic and experimental literature, which may or may not be comparable with the archaeological data. Especially in earlier studies, the source data and the cumulative error margins at the foundation of these estimations are frequently neither acknowledged nor justified, presenting a distorted impression of the accuracy of the calculated values. The units of measurement used are not necessarily consistent between publications nor standardised, making comparisons between published sources difficult, and making re-assessments of the calculations near impossible in several cases.

At the centre of many calculations of fuel consumption lie estimates of the volume of slag at a production site. Slag – the waste product of iron smelting – is archaeologically robust, and can provide a rudimentary physical measure as to the amount of iron production that was carried out in the past. However, accurately estimating the volume of slag at a site is a complex undertaking, not least because slag heaps generally comprise heterogeneous accumulations of broken and fragmented slag mixed with other cultural materials (often ceramic and stone) and lenses of other archaeological deposits (soils, mixed dump layers and so on). This renders estimating the volume of slag spread across a large site, hidden beneath the ground surface or within slag heaps a difficult task, requiring appropriate sampling methodologies tailored to each site. Furthermore, slag blocks may have been repurposed for building or road construction in the past, thus being removed from the archaeological site they originated from, and potentially leading to underestimations of production activity. Together, these factors tend to result in "hypothetical and imprecise" estimates of slag volume, and thus production levels (Arribet-Deroin 2013: 456).

Once slag volume has been estimated, the volume of charcoal required to produce that slag is generally the next component to be considered. This relies heavily on published data generated either experimentally or ethnographically (e.g. Tylecote et al. 1977; Crew 1991; papers in Nørbach 1997), which raises a new set of difficulties. More often than not, it is the fuel to ore ratio rather than the fuel to slag ratio that is reported in this literature; often the volume or mass of the slag produced in an experimental or ethnographically recorded smelting episode is not measured. Published estimations of fuel consumption also vary widely. Ethnographic reconstructions illustrate a particularly stark difference in fuel consumption between different smelting technologies, with some natural draught technologies consuming fuel at a rate as low as 1:1 charcoal to ore (Juleff 1998; Martinelli 2004) to as high as 19:1 (van der Merwe and Avery 1987), and forced draught furnaces (i.e. those operated by bellows) operating with fuel to ore ratios of, for example, 6:1 (Humphris 2010) or 4.5:1 (David et al. 1989). Smelting experiments indicate that fuel consumption can vary from smelt to smelt on the basis of the design of the furnace, the grade of the ore, the burn rate and the operating temperature of the smelt (Crew 1991; Boonstra et al. 1997; Crew and Charlton 2007; papers in Nørbach 1997). Informant interviews provide yet another form of data on fuel consumption, although this is often measured in non-standard units, for example the use of approximately one and a half trees to produce charcoal for a single smelt in central Uganda (MacLean 1994).

Further scope for imprecision is present in the calculations to convert wood to charcoal or vice versa. Published conversion factors for wood to charcoal are highly variable, based again on a multitude of experimental and ethnographic data. The variability is due to the species of wood, its moisture content (whether seasoned or fresh), the charcoal-making method used, the climate and weather, and the skill of the charcoal maker (Openshaw 1983). As such, this final stage to convert a volume of slag to an area of woodland is – like the preceding stages – fraught with scope for estimation error and lack of clarity. Gjerløff and Sørenson (1997: 69) compare three published references that approximate the yield of charcoal from wood (Buchwald 1994; Voss 1991; Monceau 1761). They use figures published in these sources to calculate that 100 kg of dry oak would produce 12 kg of charcoal according to Monceau[7] and 25 kg according to Voss – a difference of over 200%. With such variation between these estimations, deciding on the correct conversion factor to use in a particular scenario is a complicated task. Converting this charcoal estimate into an acreage of woodland is again difficult, since growth patterns are dependent on various interdependent factors specific to that location (Gale 2003: 43).

Beyond the complexity of generating an appropriate estimate for the charcoal demands of a specific smelting site, a compounding difficulty lies in estimating the past intensity of production – and thus charcoal consumption – over time. Developing a firm chronology for the lifetime of a site is critical to understanding the intensity of the wood requirement at various points in a production site's history, yet poor site chronologies are unfortunately common, especially among earlier approaches. Nor do many earlier studies examine the possibility of woodland management strategies. As wood is regenerative, estimates of wood consumption alone cannot predict landscape degradation (Eichorn et al. 2013a: 435). Practices such as controlled coppicing allow for woody biomass regeneration over time and even potentially extend the life span of

[7] However, a re-reading of Monceau (1761: 24) appears to suggest the production of approximately 29 kg of charcoal from 100 kg of dry oak; a yield of between one quarter and one third was generally expected. The original text: "32 onces de bois de Chêne très-sec, main sain, ont rendu 9 onces 4 gros de charbon". Translation: "32 ounces [c. 979 g] of very dry, but sound oak, made nine ounces 4 gros [c. 290.6 g] of charcoal". The metric conversions for pre-Revolution Paris weights were obtained from Hill (2013: 161). This 29 kg is in much closer agreement to Voss' estimation, but serves as a telling illustration of the complexity of using these sources.

certain plant species, thus enabling a sustainable industry that impacts upon a smaller area of woodland (Evans 1984; Gale 2003; Cowgill 2003; Schmidl et al. 2005).

In summary, these early studies focused heavily on the quantification of the charcoal requirements of iron production, but they were generally ill-equipped to take into account additional contributory factors such as woodland management practices, vegetation histories, forest regeneration rates or shifts in climate, and were hampered by poor chronological resolution of production activity. Other anthropogenic factors – such as cultivation and pastoralism – which are known to significantly affect vegetation structures and regeneration capacities (e.g. McGregor et al. 1992; Williams 2000) – were commonly not explored. However, the coarse models of these earlier studies offered a solid foundation for the development of more refined approaches to examining the impact of metal production (including both copper and iron) from the 1990s onwards, with an increasing number of studies led by, or having major contributions from, palaeoenvironmentalists and landscape archaeologists (e.g. Groenewoudt and van Nie 1995; Miller 1985, 1990, 1997; Mighall and Chambers 1993, 1997; Thompson and Young 1999). This involvement brought with it a new perspective that prioritised the environmental context of the industries in question. In turn, these studies began to produce results that suggested that metallurgical processes made a broader range of impacts on local environments, dependant on diverse socio-ecological factors (e.g. Mighall and Chambers 1993; Smith 1995). The impact of forest management strategies was also increasingly recognised and discussed during this period, both in ethnographic and archaeological research (e.g. Groenewoudt and van Nie 1995; Mighall and Chambers 1997; Joosten et al. 1998; Juleff 1998; Gale 2003).

Recent approaches

Over the past fifteen years, the body of literature tackling this problem has grown tremendously. The increasing trend towards palaeobotanists and palaeoenvironmental specialists working with archaeometallurgists or leading research into the ecological impacts of past industry has continued to develop (e.g. Mighall et al. 2003; Brncic et al. 2007; Butzer and Harris 2007; Eichorn et al. 2013a, 2013b), alongside an ever-increasing recognition that past metalworkers were likely to have been aware of the benefits of managing forest resources in order to mitigate against diminishing means. As Crew and Mighall (2013: 480) remind us, “there would have been a high degree of self-interest on the part of the iron workers in maintaining the woodland supply”, even more so in scenarios where a discrete group of charcoal-makers supplied ironworkers with fuel, who thus would have shouldered an independent motivation to maintain a viable supply of charcoal[8]. This trend has run somewhat parallel to debates concerning landscape change and population collapse in Central and South America, where a focus on woodland management has greatly influenced discussions of deforestation in relation to lime plaster and ceramic manufacture, agriculture and timber harvesting (Lentz and Hockaday 2009; McNeil et al. 2010; Goldstein 2011; Robinson and McKillop 2013). These recent studies not only employ a more sensitive approach to the various human demands on forest resources, they are also concerned with identifying sustainability in practice at a broad-scale, rather than attributing landscape change to a single causal factor.

Exemplifying this trend is the multidisciplinary work of Barbara Eichorn and colleagues (Eichorn 2012; Eichorn et al. 2013a, 2013b; Eichorn and Neumann 2014), who combined archaeology, archaeobotany and ethnohistory to evaluate (among other objectives) the impact of iron metallurgy on forest resources in Dogon Country, Mali. Although maintaining a similar foundation to the work discussed in the previous section – with an emphasis on calculating fuel demands based on the volume of slag present at a site – the team maximised data recovery on a larger scale than previous research. Charcoal excavated from slag heaps was used to reconstruct the surrounding woody vegetation (in conjunction with an off-site vegetation record for the preceding 9000 years), as well as to define a chronology for the sites. Appropriate conversion rates of slag to charcoal to wood were sought from the published literature to calculate possible rates of wood consumption through the lifetime of the site. Oral histories concerning vegetation and fuel choices were collected, and ecological literature on annual reproductive rates built a picture of the regenerative capacity of the forest. The authors use these data to suggest that metallurgical activity was the principle cause of vegetation change at the most intensive sites they studied, where the estimated wood consumption (including activities other than metallurgy) is thought to have exceeded the standing stock of the forest, triggering vegetation degradation in these specific cases. The sensitivity of their approach allowed them to contrast the cases of degradation they

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[8] Examples of this way of organising production activity are widespread, and abound in African ethnographies, such as the Wakamoto lineage of the Washana clan of iron smelters in Pare, Tanzania, who supplied charcoal to both smelters and smiths in the late 20th century AD (Sheridan 2001: 111), or the Dimuri specialist charcoal-makers in the Bassar region of northern Togo (de Barros 1986). In Central America, *carboneros* supplied the silver production industries of the later second millennium AD with charcoal fuel (Studnicki-Gizbert and Schecter 2010), while in England, landowners were well aware of the profitability of maintaining well-managed coppiced woodlands from as early as the thirteenth century (Rackham 2000: 89; Wheeler 2011).

documented with less severe vegetation change identified at sites where there was regular relocation of iron production centres. However, shifts in woodland composition would also have been affected by agriculture and increasing desiccation, and although these components of the vegetation system are identified, they are not accounted for in the published study.

More recent studies have applied novel methods to address similar questions of environmental impact. The geochemistry of soils and cored deposits has been explored in European and African contexts to examine metal working intensity and impact (Baron et al. 2005; Brncic et al. 2007; Jouffroy-Babicot et al. 2007; Mighall et al. 2009; Fyfe et al. 2013). Geochemical analysis of dated cores not only provides a chronological and quantifiable record of changing metal concentrations (which can be used to estimate the intensity and geographical spread of metal working through time), but pollen obtained from the same sample columns can also be used as an indicator of vegetation cover in the immediate vicinity. The benefit of this method is the immediate link between the vegetation and metalworking sequences, and it can be combined with an assessment of sustainable woodland management strategies through both on-site or off-site pollen records and on-site charcoal analysis[9] (e.g. Fyfe et al. 2013). Information contained within the pollen records can also provide temporally- and spatially-comparative data on other land use strategies (e.g. agriculture, pasture) in the vicinity of the metal industry. However, without building an independent picture of the charcoal demands of the particular metallurgical industry in question, it is still difficult to confidently establish a link between metallurgy and changes in woodland structure with this approach. As such, it should be used alongside an archaeometallurgical analysis of the metal production remains in order to reconstruct the technologies that were being employed.

An important trend in this body of more recent research is an acknowledgement of the many variables that shape the final estimations of fuel consumption and landscape change, with some researchers providing detailed meta-data for the literature that provides the basis for their estimations, and presenting a range of values of fuel consumption estimates rather than a single figure (e.g. Fyfe et al. 2013). This gives a more realistic impression of the complexities involved in making these calculations and allows for later independent interrogation of the results. Also made explicit is the

[9] Although see Out et al. (2013) for a discussion of the difficulties of assessing anthracological evidence for woodland management in the archaeological record.

difficulty in integrating the charcoal consumption rates of other production activities such as fire-setting, ore-roasting or smithing, which leave more ephemeral archaeological remains, and for which there is less experimental and ethnographic evidence of fuel consumption (Arribet-Deroin 2013). They also tend to present a more candid appraisal of the potential issues of scale and resolution in addressing the relationship between on-site metallurgical data and off-site environmental proxies, and the challenge of rectifying the chronological constraints of environmental records with archaeological records. This is most likely to be due to the greater involvement of palaeoenvironmentalists in these later studies alongside the movement towards (and capacity to) publish a higher resolution and quantity of original data, leading to a greater transparency in data analysis.

Without such input from environmental specialists, there is a risk of overstretching interpretations from complex data: "the coarse resolution of palaeoecological data has meant that interpretations often appear to be able to accommodate, or to refute, whatever theory is commonly accepted at the time" (Taylor and Marchant 1994: 284). Although these matters of resolution have improved in recent years, it is important to continue to evaluate the results of earlier research that formed the basis for enduring narratives of forest degradation in certain areas. One example is work on the intensification of early iron production in Buhaya, Tanzania (Schmidt and Avery 1978; Schmidt 1994, 1997). In this research, charcoal species excavated from iron smelting furnaces were used as a proxy for vegetation change through time alongside evidence from a poorly dated pollen core. However, without a reliable independent proxy for vegetation history[10], it is impossible to ascertain whether the changes in plant utilisation that are identified are indicative of a reduction or shift in species availability or are instead reflective of changes in resource preference (for critiques see Eggert 1987: 379, Robertshaw and Taylor 2000: 10). Although charcoal assemblages are frequently used to reconstruct past woodland compositions (cf. Marston 2009; e.g. Schmidt 1994, 1997; Eichorn 2012; Eichorn et al. 2013a, 2013b; Eichorn and Neumann 2014), assuming a non-selective exploitation strategy of all wood species locally available (as documented in Ludemann 2010, for example), the high species selectivity associated with some iron

[10] Evidence for vegetation history is offered in the form of sedimentation evidence from a core taken from the eastern part of Lake Ikimba (c. 18 km to the west of the iron production sites), conflated with palynological evidence from a core taken from Kiizi Marsh (location unknown) (Schmidt 1994, 1997). Robertshaw and Taylor (2000: 10) have criticised this approach as the Ikimba core is dated with only a single radiocarbon date, and the sedimentary environments of Ikimba Lake and Kiizi Marsh – and the area around the iron production sites – are not necessarily comparable.

production technologies recorded ethnographically[11] (e.g. Juleff 1998; Thompson and Young 1999; Mapunda 2003; Sivramkrishna 2009; Lyaya 2013) means that archaeological charcoal assemblages from these contexts have to be evaluated carefully, and preferably in conjunction with well-dated pollen records (e.g. Ludemann 2010; Crew and Mighall 2013). Furthermore, this multi-proxy approach would allow for a detailed examination of temporary or long-term changes apparent in the structure and composition of forest that might be attributable to woodland management or species selection processes related to metal production.

Future avenues

This review of previous research has demonstrated that it is challenging to confidently attribute reductions in the availability of forest resources to iron production activity alone. The high level of variation both in iron production technologies and in cultural practices of resource utilisation means that iron production cannot be assumed to be responsible for landscape degradation or change unless there is positive evidence beyond correlation. The major challenge that continues to hinder a satisfactory examination of the link between iron production and the environment is the suitability of available datasets. An overarching priority for future work should be the integration of a specialist archaeobotanical component at an early stage of research planning. As Logan (2015: 137) states, "for far too many excavations, archaeobotany is an afterthought rather than a regular incorporation into archaeological research design at an early stage … This severely limits the ability of archaeobotanists to contribute to productive discussion". Multiple, independent lines of evidence are needed to examine climatic and anthropogenic drivers of vegetation change, independent from the botanical data used to reconstruct vegetation history (Brncic et al. 2007). Reliable information on population size, vegetation composition through time, the duration and intensity of production activity, and estimates of demand and output are needed to build a picture of the resources that an iron industry required and had access to. The mitigating factors of woodland management strategies, woodland regrowth estimates, the impact of other agricultural impacts such as clearing or burning, and other pyrotechnological production activites also need to be considered to address the question: how much use can a given environment sustain whilst remaining viable as an

[11] Ethnographic sources suggest that various factors can influence the selection of different wood species for iron production, including both physical properties (calorific content, ashing behaviour, burn speed, strength) and socio-cultural associations (such as other medicinal uses).

ongoing resource? The contributory impact of climatic changes – especially shifts in precipitation, which can affect both regeneration rates and the frequency of forest fires – are still very rarely considered (although an exception is Brncic et al. 2007). Importantly, many of these factors are relevant not only to examinations of iron production, but could apply equally to the establishment and intensification of other metallurgical and pyrotechnological industries.

Unfortunately, correlations between markers of erosion and archaeological dates for iron production are still too often used to link environmental change and the impact of industry, particularly among non-archaeologists (e.g. Bayon et al. 2012a). It is rare however for a single factor to be a sole cause of environmental change. Instead, a combination of stress factors is much more likely to result in a significant long-term shift in vegetation and landscape. Any investigative approach thus needs to include an appropriate framework to integrate the ecological setting of production and the socio-economic context of the production process.

Beyond this, there is a need to understand why overly simplistic hypotheses proposing degradation and its causes have been so robustly supported. One argument suggests that the binary opposition between culture and nature – established within the principals of the Enlightenment and entrenched further with the New Archaeology (Davies 2013: 6) – positioned human action as inherently acting upon and against nature, and in doing so, degrading it (Fairhead and Leach 1996: 13). In order to move away from these constraints it becomes useful to explore landscape *transformation* rather than landscape degradation. Degradation – unlike deforestation, which implies the removal of trees and a complete conversion of the land – is a transformative state, not necessarily associated with a permanent and irrevocable change in land use. The degraded forest retains the potential to regrow (Hosonuma et al. 2012), although long-term, large-scale degradation will make recovery more difficult and delay recuperation (Thompson et al. 2013). Certainly, the regenerative capacity of some preferred fuel-wood species such as *Acacia* suggests that regrowth is highly likely after intensive industrial activity has ceased or diminished, dependent on the suitability of prevailing climatic conditions[12].

[12] In regions where *Acacia* was the preferred charcoaling species for smelting, there has so far been little discussion of the resilience of *Acacia* species and their suitability for coppicing, nor of evidence in the charcoal remains for coppicing. *Acacia* species are resistant to top-kill by fire or cutting – the stumps remain active and will re-sprout – and they have been found to re-grow to pre-harvest heights over the course of 12-14 years (with growth slowed in years of drought and

Furthermore, it is becoming increasingly clear that human modification of the environment does not necessarily result in a decrease in biodiversity. Fairhead and Leach (1996: 13) have shown that "the uses which lead to degradation in one place might lead to improvement in another"; the outcomes of such modification are variable and culturally-defined (Baleé 2013). Metal production is even thought to have stimulated a growth in forest cover in some areas: "the longest-lived of the [Scottish] highland [iron]works, caused no appreciable damage to the woods under the direct control of the furnace management, and may indeed have brought about an increase in their area" (Lindsey 1977: 63; see also Rackham 2001; Wheeler 2011). Even trees that have been coppiced continue to have protective functions, maintaining the soil as the roots remain embedded, and reducing the erosion that is often associated with a loss of tree cover. It is thus more valuable to explore *changes* in forest composition and structure that might be linked to past metallurgical industries, without presuming degradation. In each consideration of metallurgy in association with a transformation of the environment, the localised conditions and the technological approach used need to be evaluated on a case-by-case basis.

There is also scope for an exploration of the possible contributions of early intensification of metal production to global atmospheric composition. The burning of fossil fuels from the start of the Industrial Revolution is known to have increased carbon dioxide levels in the atmosphere, and the impact of this on global climate has been used as a potential definition of the start of the Anthropocene (Steffen et al. 2007, 2011; Doughty 2013). However, it has also been proposed that anthropogenic changes to atmospheric composition – and thus the start of the Anthropocene – began much earlier, due to shifts in land-use and forest cover with the advent of farming (Ruddiman 2003, 2013); it is possible that early metallurgical industries also contributed to these changes and would be detectable in global climatic records.

We have seen that recognising the agency of metalworking groups provides scope to better understand the cultural elements that govern environmental impact. Behaviour can change and adapt in response to shifts in resource availability in ways that might limit impact in the long-term. Craftspeople integrate an "acquired knowledge of local

speeded up in wetter years), providing up to c. 19,000 kg of woody biomass per hectare over a 14 year cycle (Okello et al. 2001).

ecology, resource management, and task scheduling" to select their fuel resources appropriately in changing circumstances (Goldstein 2011: 34). However, there is an upper limit on the volume of iron production that can be sustained "per unit area of forest land", even when forest management has been implemented (Wagner 2003: 33). To exceed that limit and produce more iron, a new approach must be adopted by charcoal-makers and iron-workers, prompting technological change and innovation (Tainter 2006). This could manifest as shifts in the organisation, ownership, methods or location of a technology, or the development of the use of new resources. Just how much change is permitted is dependent on other contingent factors, such as other independent stressors (e.g. climate) or social constraints that serve to limit change. It has been argued that shortages in the charcoal supply – whether brought about by human action or increasing aridity – stimulated major technological changes in past iron production technologies, such as the development of coke-fuelled blast furnaces and fineries in Europe (King 2005) and China (Wagner 2003). The forests were said to have been able to "breathe easy" after the establishment of this new technology in China (Wagner 2003: 29). Indeed, despite claims for its catastrophic impact on forest resources, iron production – often charcoal based – continued to flourish throughout the second half of the second millennium AD, in sub-Saharan Africa (cf. Evans 2015), Europe (e.g. King 2005), America (e.g. Gordon 1983) and Asia (e.g. Srinivasan 2013; Pryce et al. 2014), indicating that iron producers did successfully manage challenges in resource supply on the broad scale.

This review suggests that current evidence does not support the blanket hypothesis that iron production in isolation causes deforestation, and instead cautions that the impact of iron production – and metal production in general – was dependent on subtle variations in technological practice, socio-cultural context, ecology and climate. However, further multi-scalar evidence is needed to explore this question with a renewed perspective. Davies and M'Mbogori (2013) posit that although archaeology has to date been unable to revolutionise environmental policy making, it has been able to offer "less grand but potentially more useful perspectives on the nature of human-environment relations through time" (Davies and M'Mbogori 2013: v). The trajectory of research into metallurgy's link with the environment has taken the coarse models of earlier studies and refined them to produce increasingly realistic interpretations of industry's role in environmental change. Future archaeological work, in order to continue to extend this trajectory, should favour inter- and multi-disciplinary research, with the capacity to draw much more heavily on ecological theory and methodological advances in the study of palaeoenvironments. It should also endeavour to examine metallurgy and environmental change on multiple scales – local, regional and global – as until now there has been a dominant focus on site-level reconstructions, particularly of well-known sites of high production intensity. Archaeology's role must be to provide tangible evidence that adds weight and authority to the cultural aspects of environmental narratives, thereby encouraging more robust interpretations as to the role of industrial intensification in our ever-changing environments.

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