"Keep the Home Fires Burning": Neanderthal fuel selection as a cognitively modern process

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Citation: Knight, Rupert John Colson (2024) "Keep the Home Fires Burning": Neanderthal fuel selection as a cognitively modern process. [Thesis] (Unpublished)

“Keep the Home Fires Burning”

Neanderthal Fuelwood Gathering and Fire Use as A Selective Process

Submitted for the degree of Doctor of Philosophy in Archaeology

October 2023

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I hereby declare that the work contained within this thesis is wholly my own.

Abstract.

Despite major recent research into the Middle Palaeolithic, and Neanderthal behaviours in particular, little is currently understood of their fire use, which could have been a merely occasional behavioural trait enabled by natural lightning strikes, or a frequent behaviour necessary for survival, joined with a complex suite of pyrotechnic-dependent behaviours. In order to address this shortcoming, this thesis discusses fire use, and in particular, Neanderthal fuelwood procurement behaviours. I firstly model Neanderthal fire use across 237 sites, finding frequent fire presence but little evidence of pyrotechnic-dependent technologies. This thesis subsequently focuses on an obvious method of fire optimisation, namely choosing fuels with obvious positive burning traits, and whether these fuels were selected and curated, or gathered at random from the landscape. I find that Neanderthals displayed distinct foraging preferences for particular fuelwood genera, with certain woods far more prevalent in the charcoal record than in the palynological landscape record. Since this could result from pollen or charcoal biases, I conducted original laboratory experiments on over 40 fuelwood genera to determine genera-dependent wood-to-charcoal conversion rates which differ according to quantifiable criteria. These show that apparent Neanderthal fuel choices are unlikely to have been caused by charcoal production or fragmentation biases. Studies on genera-specific fuelwood combustion properties and replicated foraging qualities shows that preferred woods were easily transportable or high-quality fuels, and most often both. There were few instances of Neanderthals burning low-quality fuelwoods at random, which would suggest occasional expedient fire use. This thesis overall suggests that many fire-using Neanderthals were highly selective in fuelwood procurement, either selecting by fuel quality or minimising foraging effort, both models suggesting strong prior pyrotechnic experience. This understanding is of similar level to modern human hunter-gatherers, and suggests that in pyrotechnic planning, Neanderthals may have followed similar behavioural trajectories.

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Acknowledgements.

My thanks are to my supervisor, Dr Tim Reynolds, for his tireless assistance and insight into this thesis and many useful comments on its varied iterations.

This research was made possible by funding from the Arts and Humanities Research Council, Consortium of Humanities and Arts South East. My thanks are extended for their funding especially for conferences and experimental costs, and for training events throughout the pandemic.

I am extremely grateful to the Geology Department of Birkbeck College, most particularly Dr Phil Hopley and Joe Sumesar-Rai for their use of the sample preparation laboratory, and for the many conversations over the noise of the bandsaw. Likewise, my thanks are extended to the staff at the Geography Department of UCL for their use of their laboratory and furnaces, and most especially to Dr Eileen Cheng and James Shilland for their invaluable assistance for smoke removal, and post-burning cake times.

I would also like to extend particular thanks to the 2023 excavation team in Shanidar Cave for extending their invite for me to join them, and in particular to Professor Graeme Barker and Michael Hitchcock for site and landscape photographs used in this thesis, Professor Chris Hunt for invaluable insights into site palynology, and Julianna Zavodski for the best company at the 25-cent ice cream shop.

I am very grateful for particular feedback on thesis drafts and statistical analysis from Professor Catherine Clarke (aka ‘The Plumian’) and Dr Christopher Knight (aka ‘The Potamus’), aka my beloved aged Ps. My thanks also to all those who have supported me along this long journey; Elena and Veronika Everatt for hosting me in Lithuania for my cold forages there, Will Dowd and Faith Rees-Evans for making my Georgian Bath dream become a reality and surviving my thesis work with much tea and Valheim; Tom Holt for invaluable parkin and biscuit cake; Toby Bruce and Dr Molly Birch (aka ‘The Best Duo of the Amazing Trio’) for drives in the Lagonda and teas in Castle Combe; Lucy Rees-Evans for providing me a most comfortable and happy abode in 2022, and many apple crumbles, and Simon and Charlotte Bruce, for all the cakes and classic car rides over the years.

This thesis is dedicated to my beloved Italian fiancée and soon-to-be wife, Icona, for all she does for me and for her unwavering support and love of my academic mind.

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Chapter One: Introduction.

I: Fire – its value for our ancestral lineage.

Fire has long been seen as integral to human culture. Charles Darwin viewed its control as a key attribute of our evolutionary success, alongside language (Darwin 1871). Three key aspects of fire include its innate attributes, its contributions to other technologies through transformative processes, and its underlying consequences for socialisation and behavioural development. Most obviously, fire, controlled or uncontrolled, emits heat and light. Obvious to the earliest hominins on observing wildfires or lightning-strike sites, our ancestors may have followed natural fires across landscapes merely for warmth, seeing better and performing certain localised tasks for longer in the evening, and security from predators who fear fire (Attwell et al. 2015). However, it was upon understanding fire's transformative effects that its use was fully discovered. Whilst fuels fully- or partly-combust, other materials merely thermally alter structurally and/or chemically. Most obviously, foodstuffs, if correctly heated, improve in quality. Heat breaks down tough external barriers (shells) to allow access, denatures toxins (rendering wider ranges of foodstuffs edible), and breaks down fibrous foods via "external digestion" (rendering them more calorifically-valuable - Carmody et al. 2010, 2011a,b, Carmody and Wrangham 2009a,b, 2011). Archaic hominins might have observed cooking effects on underground tubers, or animals killed by wildfire, and may have used discrete areas of natural fire (e.g. burning stumps) for cooking (Bellomo 1994). However, fire also profoundly affects inorganic matter such as lithics, as well as organic food. Heat treatment (see Chapter Four) makes stone much more pliable for knapping into tools. Hominins created stone tools since 3.3Ma at Lomekwi 3, Kenya (Harmand et al. 2015), and natural fire could have been used to enhance these at any point. However, deliberate lithic heat-treatment is not noted until 65ka BP at Howiesons Poort, South Africa (Delagnes et al. 2016), and uncontrolled wildfires may not have provided suitable heating conditions for this purpose. Today, fire underpins innumerable technologies, including defence against predators, weaponisation of fire, charcoal production, metalworking, energy production, land clearance, communication, mechanisation and vehicular transport (Bowman et al. 2011).

However, perhaps more important than fire's innate properties and uses to which it can be put, are long-term effects on its users, only visible over evolutionary timescales. Firelight influences photoperiodicity and alters hormonally-controlled rhythms (Attwell et al. 2015). Blue firelight especially affects human circadian rhythms, promoting melatonin development and regularising sleep cycles (Cajochen et al. 2003). Fire use created discrete periods during evenings or nights with visibility limited to immediate fire locales, permitting certain activities (socialising, preparing/consuming food, and tool creation/curation), but not hunting or foraging over wider areas. This linked home bases and certain activities; pre-fire, homebase-specific activities would have been more limited.

This divide in activities would also have furthered development of forward-planning and socialisation in our ancestral lineage. Fire bound individuals to the static social hubs of fire pits. Communally cooking and consuming food in the evenings would have promoted resource sharing, cooperation, and more complex forms of altruism, debt and reciprocity. For effectively undertaking these activities, tool materials and food would have to be carried to home bases, rather than be opportunistically worked on/eaten ad hoc. This ultimately-efficient transportation would require picturing future fire-use, and planning materials and time needed. Modern humans understand these mental processes, but extinct hominin species might not have. The concept of "futurity", hastened by fire use, would have led to not only delay-return foraging and (ultimately) sedentary agriculture, but also, conceivably, ritual, religion, and concepts of mythical pasts and future states.

I.I: Neanderthal Fire.

This thesis examines the extent of fire use as a key technological skill in an extinct hominin species, *Homo neanderthalensis,* which flourished c.300-40ka BP throughout Europe and parts of Asia. I specifically focus on prior fuel selection behaviours, their implications and evidence in the archaeological record. Controlled fire existed long before the Middle Palaeolithic, and the earliest uncontested example is found in Wonderwerk Cave, South Africa, at 1.0Ma (Attwell et al. 2015, Berna et al. 2012), although it could have been used as early as 1.7Ma (Gowlett and Wrangham 2013). However, aside from a few other sites such as Gesher Benot Ya'aqov (Israel) c.790ka BP (Goren-Inbar et al. 2004), most early evidence comes from individual burnt lithics or charred wood, or odd fire features scattered throughout sediments. It is only in the Middle

Palaeolithic after c.100ka BP, in Neanderthal sites including Abric Romani, Kebara, El Esquilleu and Shanidar Cave, or *H. sapiens* sites like Sibudu Cave, that we see well-preserved discrete heath features. Cognitive capacities of the Anatomically Modern Human (henceforth AMH) Howiesons Poort culture c.60ka BP are well-known. Sibudu and Diepkloof contain symbolically-decorated ochre and ostrich eggshells, hafted tools made from high-quality lithics, and other evidence of 'modernity' (Wurz 1999, Wadley 2001). Cognitive (or behavioural) modernity, describing such abstract, "human" activities as religion, futurity, self and other, may have first emerged in the Upper Palaeolithic (Gabora and Smith 2018, Gabora and Steel 2020, Garogoli 2015a,b, Lombard and Hogberg 2021), although others argue that it may have been present as early as the Lower Palaeolithic (Barham and Everett 2021, Belfer-Cohen and Hovers 2010, Burdukiewicz 2014, Hovers and Belfer-Cohen 2006, Wynn et al. 2021). However, understanding "modernity" relies on comparisons with *H. sapiens'* behavioural productions which equally cognitively-advanced hominins thinking in different ways might not produce (Garofoli 2016). Neanderthal behaviours are still poorly understood. At their initial recognition in 1857, Neanderthals were described as primitive brutes, in keeping with Victorian cultural views on 'inferior' technologies and lifeways. Research throughout the last century has sought to place them more on-par with their contemporary *H. sapiens* brethren. Ralph Solecki (1975), studying the Shanidar Neanderthals, paved the way with his "flower burial" interpretation of their graves. Although this interpretation is questionable (due to pollen movement by bees or jirds – Hunt et al. 2023, Sommer 1999), modern publications still generally dwell on "behaviourally modern" aspects of Neanderthal cultures, such as care of the elderly (Spikins et al. 2018), knowledge of medicinal plants (Hardy et al. 2012) or technological lithic processes (Wragg Sykes 2015). Neanderthals were certainly complex creatures. They adorned themselves with personal ornaments, including eagle claws jewelry pendants (found in Krapina, Croatia and Cova Foradada, Spain – Radovcic et al. 2015, Rodriguez-Hidalgo et al. 2019), and raptor feather decorations (at Grotta Fumane, Italy, and Gorham's, Vanguard and Ibex Caves, Gibraltar – Finlayson et al. 2012, Romandini et al. 2016). They used black manganese oxides and red or yellow iron oxides as decorative paints (Marti et al. 2019, Soressi and d'Errico 2007), which shift frequency by cultural layer (at Combe-Grenal, France – Dayet et al. 2019). They even created permanent site structures; mammoth-bone huts at Molodova I, Ukraine (Demay et al. 2012), and stalagmitic constructions inside Bruniquel Cave, France (Jaubert et al. 2016). Given this evidence, their fire use, which was discovered so much earlier in the *Homo* lineage, should be universally accepted.

Technological comparisons between these two cousin species are easier. It is surprising how few studies discuss Neanderthal proficiencies with fire, a technology not innately demanding cognitive modernity, but arguably a prerequisite for modern sociality (Dunbar and Gowlett 2014, Gowlett et al. 2012). A particular tranche of researchers, countering current trends, attack Neanderthal behavioural modernity, either with respect to their burial customs (e.g. Dibble et al. 2015, Goldberg et al. 2013) or, more pertinently, regarding their proficiency with fire (Dibble et al. 2018, Sandgathe et al. 2011). Neanderthals could indisputably create (or at least curate) fire, as the plethora of hearths in Iberian and Near Eastern sites demonstrates. However, these authors question this technology's ubiquity, highlighting the lack of fire in certain southern French site levels and suggesting that Neanderthals could not *create* fire at will. This lack of fire could simply result from higher-altitude Iberian/Near Eastern sites having more fuelwood availability than lower-altitude northerly sites (Bujoczek et al. 2018, Komposch et al. 2022, Oder et al. 2021). However, Sandgathe's and Dibble's views eliminate fire from being a regular and important part of Neanderthal lives. In order to understand Neanderthal "cultural" capabilities, we must therefore better understand their underlying technological capabilities, amongst which fire use is an important part. The presence and use of Neanderthal fire as a technology in comparison to our fire use, and as an indicator of a selective behaviour, rather than the cognitive implications of fire use, are central to this thesis. There is, however, an underlying goal that this and other technological behaviours can in the future be considered towards building a narrative of Neanderthal cognitive capabilities.

II: Neanderthal Forward-Planning Technologies.

Fire use, in its most advanced forms, involves both selecting optimal fuel, and forward-planning for the whole burning event, to optimise (potentially rare) fire events. For fuel selection to be plausibly within Neanderthal capabilities, it would not be the only technology they used requiring selection and forward-planning, but rather should be situated alongside other such technologies. Admittedly, any technology can be novel for a species, and for the original hunting *Homo erectus* (Carrier 1984, Hora et al. 2020, Lieberman et al. 2009), fire use may have been their only behaviour requiring forward-planning. However, when a species repeatedly evidences *capabilities* for forward-planning, further behaviours requiring forward-planning becomes more plausible. Neanderthal woodworking for instance is highly plausible, given surviving evidences of their lithic-working. Several examples of complex woodworking do survive, such as the Schoeningen spears or the Pogetti Vecchi digging sticks (Aranguren et al. 2018, Curry 2024, Hoffecker 2018, Rios-Garaizar et al. 2018). Further wood-related wear on lithics (Anderson-Gerfaud 1990, Hardy et al. 2013, Viala et al. 2020) and known rarity of wood preservation allows us to extrapolate that many more originally existed. However the known complexity of Neanderthal lithic working (Muller et al. 2017, Pelegrin 2009), lithic hafting practices (Kozowyk et al. 2017, Mazza et al. 2006) and connections between lithic- and wood-working (Gurbuz and Lycett 2021) allows extrapolation even if no wooden artefacts had survived.

Many abovementioned Neanderthal traits did not necessarily require selection or prior planning. Burial was of course immediate and expedient, following (unpredictable) deaths; medicine would be gathered only when needed for particular ailments (as mobile Neanderthal groups could not store materials easily); and care of the elderly would be a constant process. Neanderthals may have planned routes between sites to take the disabled mobility into account, but this, as with most activities, is archaeologically-invisible. Often, identical activities could be carried out with or without prior planning. Selecting optimal resources could just indicate that hominins were situated in areas abundant in such resources. Two archaeological scenarios could indicate selection and prior planning:

1) Limited varieties of raw materials (lithics, food, wood etc.) found in sites where wider varieties are available in the landscape. This limited variety should represent optimisation, or *perceived* optimisation, selecting either for superior resources, ease of gathering, or distinct arbitrary selection criteria (which may not represent functional optimisation). Selection is further indicated if resources are far from initial procurement sources.
2) Caching behaviours of raw materials or tools. Assuming recurrent site use for individual Neanderthals, caching would indicate intentions to return and collect the items later.

Optimal or high-quality raw materials are found in many Neanderthal sites. Lithics are an obvious example; however Neanderthal sites are often deficient in this regard. Mousterian lithics were gathered extremely locally; 90% of lithics in caves, and up to 100% of lithics in open-air sites are from within 10km (Aubry et al. 2016, Pettitt 1995). This is frequently noted; the following sites in Table 1.1 are but a few examples:

Table 1.1: Middle Palaeolithic sites containing predominantly local lithics.

Region	Site	Reference
Iberian Peninsula	Abric del Pastor	Machado et al. 2013
	Abrigo de la Quebrada	Eixea et al. 2014
	Abrigo del Molino	Kehl et al. 2018
	Cova del Rinoceront	Daura et al. 2015
	El Salt	Machado and Perez 2016
	Galeria de las Estatuas	Arsuaga et al. 2017
	Gran Dolina	Blasco et al. 2010
	La Guelga	Menendez et al. 2017
	Navalmaillo	Marquez et al. 2013
	Prado Vargas	Navazo Ruiz et al. 2021
	Teixoneres Cave	Rosell et al. 2017
	Valdegoba	Quam et al. 2001
	Zafarraya	Hublin et al. 1995
France	Bettencourt-Saint-Quen	Clark 2015
	Bout-des-Vergnes	Courbin et al. 2020
	Combe Brune	Frouin et al. 2014
	Fresnoy-au-Val	Clark 2015
	Grotte de la Verpilliere II	Frick 2016
	Le Prisse	Cologne et al. 2015
	Noisetier Cave	Mallye et al. 2012
	Villiers-Adam	Clark 2015
Italy	Grotta Breuil	Grimaldi and Spinapolice 2010
	Grotta dei Moscerini	Villa et al. 2020
Germany	Geissenklosterle	Conard et al. 2019
	Konigsaue	Weiss 2015
	Lichtenberg	
	Neumark-Nord	
	Pouch-Terrassenpfiler	
	Salzgitter-Lebenstedt	
Eastern Europe	Cioarei-Borosteni	Carciumaru et al. 2002
	Il'skaja	Hoffecker et al. 1991
	Ksiecia Jozefa	Zieva et al. 2008
	Pietraszyn 49a	Wisniewski et al. 2019
	Vindija	Ahern et al. 2004
Near East	Boker Tachtit	Goder-Goldberg et al. 2017
	Dederiyeh	Nishiaki et al. 2012
	Emanuel Cave	Goder-Goldberg et al. 2012
	Kunji Cave	Baumler and Speth 1993
	Shi'Bat Dihya	Sitzia et al. 2012
	Teshik-Tash	Nishiaki and Aripdjanov 2020
	Umm el Tlel	Lourdeau 2011

Others show mixed procurement, with some local but other intermediate (30-100km away) lithics; in France (Baume-Vallee, Bordes-Fitte, Cassenade, Chene Vert, Combe-Capelle Bas, Les Pecheurs, Les Pradelles, Payre – Aubry et al. 2012, Baena et al. 2014, Costamagno et al. 2006, Dawson et al. 2012, Discamps et al. 2019, Moncel et al. 2008, Raynal et al. 2012, Roth and Dibble 1998), Italy (de Nadale, Riparo Bombrini – Holt et al. 2019, Jequier et al. 2015), the

Iberian Peninsula (Arlanpe, Jarama VI – Kehl et al. 2013, Rios-Garaizar et al. 2015) and Eastern Europe (Karabi Tamchin, Kulna, Raj Cave, Velykyi Glybochok, Weasel Cave – Doronicheva et al. 2019, Lanczont et al. 2014, Neruda 2017, Patou-Mathis 2004, Yevtushenko et al. 2003). A few sites use minimal local lithics, and only higher-quality distant ones (>30km); this is noted in Axlor (Gomez-Olivencia et al. 2018) and El Cuco (Gutierrez-Zugasti et al. 2017).

This suggests that Neanderthals may have been somewhat selective of their raw lithics, but not to the extent of AMH. This behaviour may be masked if Neanderthals already lived near high-quality raw lithics and procured them locally (as at Aguilon – Mazo and Alcolea 2020). However, technological optimisation is present. At Kabazi II, tools were partially reduced before being brought to site, reducing loads and suggesting keen forward-planning (Uthmeier 2006). Furthermore, Neanderthals may have deliberately selected home-bases close to lithic sources (Sisk 2011), thus masking selection by distance *from* the sites. Other materials were procured or curated over great distances, either within a group or through inter-group exchange (Mellars 1996). A key example is obsidian, a valuable rock which could be knapped into extremely thin, sharp blades. Whilst mostly used since the Upper Palaeolithic, Neanderthals selected obsidian at Ortvale Klde (125km away - Le Bourdonnec et al. 2012), Kulna (400km away – Moutsiou 2011, pp.155-156), Mesmaiskaya and Saradj-Chuko (from 200-250km east – Doronicheva and Shackley 2014, Doronicheva et al. 2019). In the last site in particular, obsidian formed 97.8% of the assemblage in layer 6B (Ibid). Neanderthals also imported non-local jasper at Grotta Romanelli, Grotta dei Giganti, Grotta Uluzzo, Grotta Mario Bernardini, Grotta Torre dell'Alto (all Spinapolice 2018), La Crouzade (Saos et al. 2020) and Ramandils Cave (Rusch et al. 2019). Bitumen was also procured 40km away from Umm el Tlel (Boeda et al. 2008a,b).

These all suggest that Neanderthals certainly *could* gather selectively for valuable materials. Neanderthals also required famously high-quality diets (energy-rich foods such as fatty meats and carbohydrates which posed minimal risk of food-transmitted illness or nutritional deficiencies), and appeared extremely selective in dietary procurement (Power 2019). Certain sites appear highly selective towards specific prey species (e.g. Caucasian tur, *capra caucasica*, at Ortvale Klde – Alder et al. 2006); others show wider dietary breadth (e.g. Djruchula Cave – Adler and Tushabramishvili 2004). Despite increasing recognition of Neanderthal plant-based diets (Hardy et al. 2012, Henry et al. 2014), Neanderthals were obviously sophisticated hunters, killing megafauna such as woolly rhino, mammoth and elephant (Gaudzinski-Windheuser et al.

2023, Germonpre et al. 2014). Many sites are extremely monospecific; Neanderthals at Mauran, Les Pradelles and Riparo Tagliente hunted almost exclusively bison, reindeer and roe deer respectively (Rendu et al. 2012, Vettese et al. 2021). Hunting single species advantageously tailoring each group's hunting tactics to a specific prey type. Amongst specialist Neanderthal groups, which may not represent the whole population, these behaviours not only increased hunting efficiency but would also have helped prevent neighbouring groups competing for identical resources. This only would help however where specialist groups lived close together, and risked exhausting environmental resources. Neanderthals may well have selected sites close to preferred prey herds, following them throughout the year. Neanderthals would not have encountered these species by chance; they would have determined encounter spots, ambush locations along known migration routes to disadvantage the prey (Adler et al. 2006). Many such prey were dangerous, as shown by frequent injuries survived by Neanderthals including La Chapelle 1, La Ferrassie 1 and 2, Tabun 1, Shanidar 1 and 3, Neanderthal 1, Krapina 37 and 180, St Cesaire 1 and La Quina 5 (all reviewed in Spikins et al. 2018). These (healed) fractures doubtless resulted from close-quarter hunting practices, as indicated by kill marks on prey species (Gaudzinski-Windheuser et al. 2018). Given size disparities between Neanderthals and megafauna, forward-planning and group cooperation would have been especially important during hunting.

A further key aspect of Neanderthal hunting, which increasingly developed from 250,000BP onwards (Lazuen 2012, Stiner 1991) is the selection of prime-age individuals. Whereas hunting weaker immature or elderly individuals is potentially easier, there is less meat per kill and it is of a lower quality, with low intramuscular fat levels in immature individuals, and low fatty acid levels in old individuals (Lorenzo et al. 2019). Attacking prime prey was much riskier but more rewarding; Neanderthals show this pattern with many prey species, including aurochs, bison, reindeer, mammoth and caprids (Boismier 2003, Gaudzkinski and Roebroeks 2000, Farizy et al. 1994, Jaubert et al. 1990, Roebroeks and Gamble 1999 – all reviewed in Adler et al. 2006). An alternative strategy of killing only mammoth calves is seen at Spy, Belgium (Germonpre et al. 2014), and that of killing pre-injured individuals at Lynford, England (Schreve 2006). It is unknown whether they separated and killed only these individuals, or more indiscriminately killed prey but subsequently butchered and transported only prime meat cuts (White et al. 2016). Neanderthals also were extremely selective of the animal *parts* they butchered and removed to site to fillet; they selected meat-bearing limb bones and rejected ribs (Marin et al. 2020), the latter not being found on site. Transport concerns were obviously considered, and prime meat cuts easily recognised and removed in the field. Overall, many Neanderthal hunting and butchery practices show undeniably selective processes, as well as “the use of a sophisticated weapons technology, group coordination and anticipatory behaviour, and an intimate knowledge of prey behaviour” (Adler et al. 2006, p.96).

Finally, Neanderthals displayed occasional caching behaviours; key indicators of forward-planning and optimisation, but notoriously hard actions to identify. As White and Pettitt (2011) say, “caching implies not only the deliberate postponement of action – members of task groups storing objects for an anticipated return visit – but also the provisioning of sites, transforming them from spaces into places”. Artefact collections are not enough; they may represent in-situ production/recycling sites, or post-deposition water transportation to single locales. Later (ritual) caches may be buried in pits, but Neanderthals are not known to have ritually deposited. Lithic caches should contain workable (or repairable) tools which could be recovered, with no in-situ knapping events around them, and containing too many artefacts to represent random accidental loss. However, ideally these caches would of course have been rediscovered and dispersed, and the few remaining would represent where the owners forgot them or were prevented from recovering them. These caches are found in Haldenstein (Bolus 2004), Arts Bogdyn Nuruu (Masojc et al. 2019), Tolbor (Derevianko et al. 2004), Mount Pua (Barkai and Gopher 2011), Kabazi V (Veselsky 2008), Soucy 1 (Lhomme et al. 1998), Grotte Vaufrey (Peresani 2009, Rigaud 1988), Cogyan Cave and Kent’s Cavern (White and Pettitt 2011).

Overall, these evidences suggest that Neanderthals had many forward-planning and selective behaviours. Although not selecting all lithics, many Neanderthals selected rarer harder-to-procure lithics for occasional tools, and they were often extremely dietarily-selective, by species (megafauna), age (prime) or body part. Neanderthal technologies, especially their lithic reduction sequences and hafting adhesive preparation methods, may have involved prior planning and understanding of future events from previous sources, but it is notoriously difficult to reconstruct technological processes from only the products. Finally, Neanderthals also cached lithics; we naturally miss many lithic caches, and other organic caches would not have survived. These evidences all indicate that Neanderthals had the *capacity* to be selective in their fuel choice, and understand future consequences of current selective actions.

III: Research and Questions Proposed.

This thesis challenges the hypothesis of fireless Neanderthals, not by providing further evidence of presence or absence of fires (as this is fraught with risks due to extreme archaeological losses from this era) but by suggesting that the fires created were more complex than previously thought. Complex, regular fire use, as opposed to odd expedient experimentation, suggests a familiarity (at either group, regional or species levels) with fire. Familiarity cannot easily be acquired without multiple prior trials, perhaps over many generations, which may subsequently have been lost; a few technologically-advanced fires in sites otherwise containing long uninterrupted periods of Neanderthal occupation, may suggest other lost fire layers. Not all fires suggest other missing ones however, and especially not single simple fires.

I define “complex” fire as being composed of five features (see p.104-106); lighting fires, hearth preparation, performing fire-specific activities on hearths, optimising fuels for specialist functions, and extinguishing fires post-use. Neanderthals are not known for prepared fireplaces; they had no pit-hearts or stone-ring hearths, instead burning directly on the cave floor, and fire extinguishing is archaeologically-invisible. Neanderthal firelighting skills and fire-dependent activities, most notably cooking and lithic heat-treatment, have been studied in many other ably-argued papers (see Henry 2017, Agam et al. 2023 etc.), and are covered in Chapters Three and Four respectively. The main focus in the remainder of this thesis is on the fuels being used, which also forms the core parts of my practical experiments.

I concentrate on fuels used partly because fuels, as charcoal, are the best-preserved aspects of fire, even if hearth features themselves are lost and scattered, and partly because of the role of fuel selection in indicating this “choice” and “forward planning” integral to modern lifeways. Hearths are mostly wood-fuelled, but may also use other sources; Neanderthals may have also burnt dung (Henry 2017), bone (Yravedra and Uzquiano 2013) and coal (Thery et al. 1996). However, wood was by far their most common fuel. The important question I address is *which* woods they burnt, and whether this use corresponds with landscape availability or with particular benefits of the woods themselves. Shackleton and Prins (1992) introduced the compelling “Principle of Least Effort” model, by which hunter-gatherers gather fuel which is most easily available, regardless of quality. Thus the proportion of genera in fuels (and thus in charcoal) directly corresponds to landscape vegetation proportions when it was gathered. Most papers reconstructing past environments from anthropogenic charcoal implicitly or explicitly follow this model. Shackleton and Prins' model is notably based on modern hunter-gatherers; and therefore proves that fuel choice is not an *essential* prerequisite for AMH, as some *H. sapiens* today choose fuelwoods randomly (e.g. Alix 1998, Dufraisse et al. 2007, Kefa et al. 2018), especially as byproducts of other activities (e.g. forest clearance - Picornell-Gelabert 2020). Nonetheless, educated fuel choices are impossible *without* understanding combustion technologies and having previously tested fuels, to understand which ones best suit which purposes. As Chapter Nine demonstrates, fuel properties (burning duration, light output, heat emitted etc.) are not directly visible from the fuels themselves; in order to know fuel properties, they must previously have been burnt, theoretically over long time periods. I propose that Neanderthals did not necessarily follow the Principle of Least Effort, and may have chosen fuels according to other criteria, such as light emitted, burning duration, or lack of smoke produced, or how easily it could be broken off and transported.

Furthermore, specific fuelwood selection suggests a form of optimisation – these fires would probably still ignite and burn with other, more commonly-available fuels, but Neanderthals might deliberately choose particular high-quality fuels, optimised for specific functions, at potentially higher foraging costs. This optimisation, in turn, may suggest more advanced uses of fire, for which certain conditions are sought. If Neanderthals used hearths for lithic heat-treatment (see Chapter Four, p.110), they might want slow-burning fuels, and choose wood such as *Quercus* spp (see Table 9.6, p.261). Alternatively, they may want maximum lighting effects, and thus burn *Betula* (Table 9.8, p.265). The fuels used therefore influence and act as proxies for fire-based activities, even if these naturally-ephemeral activities have been lost. Thirdly, selecting optimal fuelwoods suggests some form of forward-planning. Neanderthals would not be able to rely on the *nearest* fuelwoods, accessed immediately before the fire's commencement, but must have collected firewood throughout their daily travels, in anticipation of the evening.

However, this Principle of Fuel Optimisation is not without pitfalls. In landscapes dominated by optimal fuelwoods, this selection process would be indistinguishable from the Principle of Least Effort. Certain fuelwoods may also be optimal for several functions (e.g. light and heat output often closely correlate). Furthermore, much Neanderthal charcoal is found scattered throughout sediments, although several discrete hearths remain. In palimpsests without discrete hearths, it is unknown one fuelwood genus or multiple genera were burnt together. Finally, it has been noted that fuel properties sometimes depend less on taxonomic genus, and more on age, condition (dry/green, wet/dry) and size (Chabal 1992). However, these qualities, and those of branch drop, decay and stand regeneration, may also be species-dependent.

With this in mind, I examine relationships between fuel use and environmental availability by plotting charcoal against pollen within Neanderthal sites, extending my 2019 Masters' data (Knight unpubl.) to more sites. This previous study compared aboreal pollen levels, representing natural background environmental signals, with charcoal, representing fuelwoods which Neanderthals chose and burnt. I found that many fewer genera were being burnt than were potentially available in the landscape, and that there was an almost ubiquitous selection towards *Pinus* spp., whilst *Betula* and *Quercus* spp., although still utilised, were burnt less than expected given their environmental availability. Other genera were burnt in very small proportions, possibly as expedient fuels. However, charcoal does not perfectly represent fuels burnt, and pollen does not perfectly represent past landscape flora. Certain fuelwood genera may produce more charcoal than others when burnt, and likewise, wind-pollinated genera produce far more pollen than insect-pollinated ones. A natural critique would be that these two factors alone create artificial differences between anthracological (charcoal) and palynological (pollen) datasets. Consequently, I create experimental procedures exploring these issues and re-calibrate my initial calculations. If these objections can be removed, the most plausible remaining theory, that these differences directly result from Neanderthal fuel choice, must remain. Throughout this thesis I address several important research questions:

What evidence is there that H. neanderthalensis used fire commonly as a species, and particularly used it to facilitate other technologies (advanced fire use).

Did Neanderthals select specific fuel genera for their combustion properties, or did they choose indiscriminately according to the Principle of Least Effort?

Do patterns of fuel use and specific choice of optimum fuels stand up to critique when confusing effects of differential charcoal and pollen production by fuel genera are taken into account?

In order to investigate the second and third questions, I have a number of sub-questions associated with their methodological aspects:

- *Do different arboreal genera create different amounts of charcoal?*
- *Does charcoal of different genera fragment at different rates under identical taphonomic conditions?*
- *Do different arboreal genera create significantly different quantities of pollen?*
- *With all factors taken into account, do my initial charcoal-versus-pollen comparison findings change significantly, and are these findings in line with our current understanding of other aspects of Neanderthal life?*

IV: Chapters.

Chapter Two reviews Neanderthal fire use and how we can detect it. It focuses not only on obvious charcoal, ash layers and surviving heath features, but also on more ephemeral heat-altered lithics and animal bone, sediment magnetism and rubefaction. I counter the objections of Goldberg, Dibble, Sandgathe etc. against widespread Neanderthal fire use, concluding that their studies are site-specific. Apparent absences of Neanderthal fire are explained through sites not having modern scientific techniques available upon initial excavation, or that proxies used missed ephemeral fire use. I compile several proxies which may indicate the presence of fire, especially where multiple proxies are found together.

Chapter Three statistically models these proxies in over 230 Neanderthal sites, showing that over 80% of Neanderthal sites containing some form of fire proxy. Differences between Neanderthal cave and open-air site fire frequency emerge through different taphonomic processes or fire practices. There are few pan-European geographical trends, indicating that fuelwood availability varied little by latitude, and its scarcity did not prevent northern fire use. This suggests that, in answer to my first research question, Neanderthals commonly used fire, increasing the possibility of pyrotechnic-dependent technologies.

Chapter Four examines pyrotechnic-dependent technologies (cooking, hunting, site maintenance, lithic heat treatment and melting adhesives), and their signatures in the Neanderthal record. Palaeolithic cooking is almost indistinguishable from burning of organic refuse. Other cooking evidence, based on altered foods in dental calculus, isotopic studies, and genetics, supports Neanderthal cooking (from genetics, potentially at population levels). Neanderthals rarely heat-treated lithics; however, reviewing the benefits and downsides of heat-treated tools, this may not represent a behavioural inability, but rather an active avoidance of this technology. Neanderthal hafting technology is rare but present (e.g. Wragg Sykes 2015). However, Schmidt et al. (2019a) sufficiently refute apparent "technological complexities" of this technology, and other evidence suggests that some apparent "adhesives" are just accidentally-precipitated pyrotechnic byproducts. Overall, some limited evidence of advanced fire functions remain, but most activities leave minimal initial evidence. Therefore, the most advanced pyrotechnic task may have been fuelwood procurement, which may be the only viable method for studying detailed Neanderthal fire-related behaviours.

Chapter Five discusses various Neanderthal fuels, and concepts of "choice" and "selectivity" through desired fuel traits and ethnographic wood-gathering insights. I also discuss the "Principle of Least Effort" model, its value and how its innate assumptions can not only disguise personal choice, but also severely hinder palaeoenvironmental reconstruction from anthropogenically-altered material. My 2019 Masters' data compared charcoal to pollen to detect fuelwood selection in five Iberian sites, finding distinct selective practices. Pollen recalibrations, to determine if differential genera-specific pollen production causes bias, shows that wind-pollinated trees produce much more pollen than insect-pollinated ones, forming most of the pollen and charcoal records. When my Masters results are recalibrated and compared however, discrepancies between charcoal and pollen are still further *increased,* strongly suggesting that pollen production biases may mask Neanderthal selection practices.

Chapter Six introduces my experimental methodologies, which investigate whether differential charcoal production and fragmentation by genus (under otherwise equal conditions) explain discrepancies between these complementary anthracological and palynological diagrams, or whether active Neanderthal selection is more probable. I discuss factors of charcoal yield (wood size, density, moisture content, ash content, temperature and duration of burning) as well as insights from previous studies, and relative merits of real-life versus laboratory studies. I describe my two experiments (on wood-to-charcoal conversion rates and charcoal fragmentation patterns respectively), the wood samples, equipment and techniques used.

Chapter Seven presents my experimental results. The first experiment, investigating wood-to-charcoal conversion rates, found highly varying genera-specific charcoal yields at 350°C and 700°C. At 350°C, conifers produced more charcoal than deciduous/ evergreen trees, although evergreens produced the most at 700°C. Comparisons with six other similar studies showed many similarities, with differences mostly ascribable to different methodological choices. My second experiment, on charcoal fragmentation rates, showed much more variety; 1g of charcoal created between 6 and 71 identifiable fragments, with inter-genera variety correlating with charcoal density. Overall, genera-specific charcoal conversion rates are more reliable biasing factors in archaeology than differential fragmentation rates (which depend on too many variables to accurately understand or predict).

Chapter Eight applies these results to recalibrating charcoal values of twenty-nine Middle Palaeolithic sites. I look for fuel choice in seven sites with complementary pollen and charcoal records, finding that recalibration does not decrease discrepancies between the two datasets, and conclusively ruling out differential charcoal production as a cause of the discrepancy between fuelwood proportions in fires and their landscape availability. However, differential charcoal fragmentation may be partially responsible. The other sites give insight into which fuelwoods Neanderthals burnt, and general Middle Palaeolithic arboreal composition and landscape types.

Chapter Nine examines chosen fuelwoods through two metrics; innate wood properties (ash content, density, calorific value, fuel value index, and wood strength), and their properties when burnt (burning duration, and light and heat output). Neanderthals paradoxically appeared to select low-calorie woods, probably representing an artefact of differential preservation. Examining papers by Thery-Parisot et al. (2014) and Hoare (2020), all woods burnt as regular Neanderthal fuels scored highly, and harder-to-burn fuels (e.g. *Alnus*) were universally avoided. Although local availability usually determines primary fuelwoods (Neanderthals would not search for pine in juniper-dominated landscapes), Neanderthals never burnt *all* fuelwoods according to availability, but rejected certain fuel genera. This required detailed ecological knowledge, understanding of fire and fuel use, and forward-planning abilities. Furthermore, chosen fuelwoods were often also “good” fuels with both high heat and light outputs, making motivations for these choices unclear.

Chapter Ten builds on Chapter Nine by providing further information on preferred fuels and landscape types. Through replicated foraging experiments in five landscapes, representing Middle Palaeolithic site locales, I examine potential foraging patterns based exclusively on ease of gathering. Many rare or missing Neanderthal fuelwood genera were evidently rejected from difficulty of harvesting (e.g. gorse). Common fuels, including *Pinus* and *Larix,* were easy to gather, as well as being highly-regarded fuels, and selectable on either criterion. However others (*Picea* and *Juniperus*) were easy-to-burn but hard-to-gather fuels, and their selection represents direct positive selection for combustion qualities, at higher foraging costs than other woods. Combining information from Chapters Nine and Ten builds up site- and fuel-specific narratives of how different Neanderthal groups approached fire use, and the implications of these behaviours for our understanding of their technological abilities and similarities to our own species.

Chapter Eleven concludes this thesis, summing up all evidence of Neanderthal fire use, especially aspects of advanced pyrotechnic technologies. I conclude that studying fuel choice and procurement greatly adds to our knowledge of our closest extinct evolutionary relatives. The difference between charcoal and pollen records, and the systematic removal of potential explanations due to differential charcoal and pollen production by different fuel genera, leaves active Neanderthal choice as the most likely explanation. The burning values of various fuelwoods, along with their ease of procurement in simulated Middle Palaeolithic landscapes, suggests regimes of procuring high-ranking fuels as primary fuels, supplemented by occasional other (expedient) genera, universally avoiding abundant fuelwoods with few favoured burning traits. This pioneer study of individual fuel procurement behaviours *by genus* adds to our understanding of Neanderthal fire use, which in some aspects was as sophisticated as our own.

Chapter Two: Review of Middle Palaeolithic Fire Use.

Fire, described by Charles Darwin as "probably the greatest ever discovery made by man, excepting language" (1871, p.137), is a destructive natural force which, when harnessed by intelligent hominins, has become key to evolution and modern life. It not only enhances survival, but also drives behaviour, technology, sociality even evolution. Contrary to Darwin's initial statement, it was not even Man (as in *Homo sapiens*) who first used fire, but rather archaic ancestral hominin species. Zhong et al. (2014) claim it was *H. erectus*, and fire may have driven the transition from *Homo erectus* to modern *Homo sapiens*, although evidence for initial fire use is patchy (Gowlett 2015, James 1989). One particular ancestral species, *H. neanderthalensis,* commonly known as Neanderthals, survived almost 250,000 years in tough, rapidly-changing conditions in partially-glacial Europe. These hominins were advanced compared to their predecessors, hafting lithics and hunting large, dangerous game including mammoth and woolly rhino (Smith 2015). They may even have had several behaviourally-modern traits, including building construction, ritual/religion and burial (Demay et al. 2012, Garcia-Diez 2022, Jaubert et al. 2016, Rendu et al. 2014, Romandini et al. 2014, although see Gargett 1989 for early counter-claims and Garofoli 2017 for modern ones). Fire could have been important for Neanderthal behavioural repertoires, and some groups used it commonly, but the extent of its use at population levels, and whether this use was planned or expedient, is poorly understood.

The first two chapters address the first question; how common was Neanderthal fire (as well as briefly examining whether Neanderthals could *start* fires). Later chapters discuss pyrotechnically-dependent technologies, and fuel choice. To understand Neanderthal fire however, we must understand earlier fires, as *H. neanderthalensis* was not the first fire-user. I analyse various fire proxies in the archaeological record, the advantages and downsides of studying each, their various taphonomic durabilities, and the expectations of what may be found under different circumstances.

I: Natural and Anthropogenic Fire.

Natural fire has been present on earth since plants have existed as fuel. Charcoal has been found in Devonian rocks from c.400Ma (Stahlschmidt et al. 2015). During the earth's formation, and occasionally in modern times, volcanic eruptions and meteor strikes caused the most fire. During hominin evolution, most natural fires were caused by lightning strikes (Dowdy and Mills 2012, James 1989). Lightning is a common natural phenomenon; in modern-day Alaska, which has similar temperatures to Middle Palaeolithic Europe (Bolland et al. 2021), lightning ignites up to 100 fires a day, which burn for up to 20 days (Gowlett 2016). Alaska, being c.1.7 million km^2, is vastly larger than the Iberian Peninsula's 0.58 million km^2, but glacial Iberia could still have generated up to c.34 fires per day.

- A FAS wildfire project from 2013-2022 calculated that an average 61,410 wildfires destroyed 7.2 million acres annually (Congressional Research Service 2023).
- Each wildfire therefore covered, on average, 0.18 square miles.
- In Iberia, 34 wildfires a day equates to 12410 a year. Thus 5785.5 km^2, or 1.01% of the landmass, would have been burnt by a wildfire in the last year.
- However, as each burns for only 20 days, at any given time only 317km^2, or 0.05% of Iberia, would be actively burning. This naturally varies by season.
- There would then only be a 0.05% chance that an individual area would be on fire at once. However of course, wildfires smoke and are very visible from far away.

Neanderthals had smaller daily foraging radii than AMH, often only c.5km (Henry et al. 2015), equating to an area of 78.5 km^2. This meant that for a given site, there was a 3.9% chance that a wildfire would be around it at any given day.

This low figure may still have been sufficient for exploitation by archaic *Homo* species. This figure increases in warmer, drier climates where more dry, dead undergrowth can ignite, although open deserts naturally lack fuel to burn. This undergrowth is not uniformly distributed across landscapes, nor are areas of lightning strikes. Wildfires, although dangerous when aflame, serves many functions once smouldering. Naturally cooked animal corpses and subterranean plant tubers can be scavenged. Fire-ravaged landscapes provide high-quality, ash-rich soils for plant regrowth, favouring shorter shrubs with edible berries or bark, which were previously shaded and outcompeted by tall, mature trees. Fresh buds and shoots would attract prey animals including deer, and post-fire landscapes would be more open for hunting with projectile weapons. And finally, the fire itself, if still burning in places, might be used by an intelligent animal for warmth, protection from fire-fearing predators, and perhaps even for cooking food.

A hominin such as *Australopithecus* or early *Homo* could have benefitted immensely from opportunistically following wildfires around the landscape, and this may represent the first fire use (Gowlett 2016). Elemental carbon studies in deep-sea cores suggest that natural landscape fire dramatically increased around 400ka BP (Bird and Cali 1998), correlating with drastic increases in number of controlled fires. However, much earlier evidence of anthropogenically-influenced natural fire exists. *Australopithecus* would not have ignited, fuelled, spatially-limited or extinguished fires (Burton 2009). It is doubtful whether such usage can be considered a technology yet. Whether it was practiced at a species/genus level is also unknown, as this use is archaeologically invisible. Even wildfires with archaeological inclusions, could be wholly natural; and burnt food inclusions could have been burnt naturally or introduced by hominins.

II: Earliest Fire Use.

The first fire traces are extremely ephemeral, and it is difficult to tell whether they represent a) wildfire, b) controlled, curated wildfire subsequently limited to particular “hearth” spaces until it expired, or c) fires started, controlled and extinguished by hominins. To search for true fire use, we need to look at the latter. True control of fire and the *Homo* lineage emerged together. Fire use is first evidenced at FxJj 20 Main at Koobi Fora (1.6Ma), contemporary with *H. habilis, H. erectus* and *H. ergaster.* Oxidised, burnt sediments here formed focal points for lithic knapping, although no lithics or tools were burnt (Attwell et al. 2015, Bellomo 1994). The contemporary Chesowanja site contains burnt clay associated with an Australopithecine cranium (Gowlett et al. 1981, 2023). However, this early fire evidence is very doubtful. It is unknown exactly how burning tree stumps creates pseudohearths (Sandgathe 2017), but such burning hearths could be used, without further preparation, as cooking fires (Attwell et al. 2015). Koobi Fora, and related sites like Ologesailie and Bodo have hearth-like depressions containing stones and bones, but without charcoal (Hlubik et al. 2017, Isaac 1977).

Real control of fire is not evidenced, sensu stricto, until 1Ma at Wonderwerk Cave, South Africa where burnt bones and charcoal are observed (Attwell et al. 2015, Berna et al. 2012). It is next found c.800ka BP at Gesher Benot Ya'aqov (Alperson-Afil 2008), with proper layered hearths. The former sites may represent fire *use*, but here represents *curation* of fire. *Manufacture* of fire may be still later and exclusive to *H. sapiens;* however *H. erectus, H. heidelbergensis and H. neanderthalensis* certainly curated fires. Unlike earlier African sites, these later Neanderthal sites are frequently in caves where wildfires are unlikely to have reached. Guano-filled caves can potentially combust, although this is unlikely (Lundberg and McFarlane 2021) and Neanderthals may have avoided these unhealthy environments. Shanidar Cave remained unburnt despite recent wildfires in 2019 (Hitchcock, pers. comms., though see James 1989 and Zafren et al. 2005 for reviews of direct lightning strikes into caves). This indicates that if not manufactured, fire was carried to caves on torches, whereas earlier sites were deliberately located near pre-existing fire. Moving fire to caves would also require transporting fuel to feed it, whilst earlier African fires, if deliberately fuelled at all, could have been done so expediently from very immediate surroundings. In my opinion, this change of location, controlling where fire is rather than being guided by natural causes, and integrating fires into residential camps rather than vice versa, defining *the* first controlled fires. Create fire is of secondary consequence to being able to move it, although having ignition technology makes the process much easier, completely breaking links between 'natural' and 'domestic' fires. Of course, this may also have happened at earlier African sites, but the evidence is less visible until fires start occurring in caves.

II.I: Problems with studying early fire use.

Another question is the universality of fire technology. Just because fire is used by one *Homo* group, does not mean that all members of that species could or did use fire. There was never a single point in prehistory where fire was suddenly universally adopted and then used everywhere (Sandgathe 2017), but it was rather adopted intermittently, potentially being lost and re-discovered. Even within a group, certain individuals may have used it and others not. If fire was not essential for survival, but rather a subsistence benefit, there would be individual advantages from its use, but no great group disadvantage from not using it. Individuals cooking on curated fires and creating higher-quality cooked food may appear more attractive mates and thus have higher reproductive success (as superior resource provision increases reproductive success – Alley et al. 2013, Li et al. 2002). This technology was then probably learned by their children. However, in Africa where reliance on fires for heat is less necessary than in colder climates, fire-using and non fire-using groups would not appear much advantaged or disadvantaged. Changes occur only over evolutionary timescales, where fire use allows larger brains and loss of body hair to further develop (Attwell et al. 2015, Pagel and Bodmer 2003, Wrangham and Carmody 2010). Bipedalism likewise developed alongside fire; it was another energy-saving adaptation alongside cooking to extract more energy for large brains (Ibid), and freed up hands for fuel gathering (Medler 2011). Natural fire and lava flows may even have necessitated walking upright on hot ground. A widely-dispersed species such as *H. erectus* would have some groups more optimally located for finding natural wildfires and fuels than others. Certain groups would also need fire (particularly its warmth in cold landscapes) more than others.

Sandgathe et al. (2011, in Shimelmitz et al. 2014) define fire use as only being habitual once it is permanently found across many contemporary sites sharing other technological and cultural features. Sandgathe uses this definition to argue that Neanderthals were not habitual fire users. The difficulty with this, archaeologically, is that contemporaneity is hard to establish, and taphonomic processes increasingly obscure evidence through time, selectively preserving more durable evidence such as lithics. Thus, even if fire had been used at uniformly high levels since the earliest Lower Palaeolithic, a) fewer older sites would remain, and b) proportionally less fire evidence would be found in each older site. Glaciation also destroys European prehistoric sites in distinct spatial-temporal patterns (Gowlett 2006). The initially fire evidence is almost certainly lost; these may have included hearths (comprised of burnt sediment, ash and charcoal), burnt lithics and burnt bone. Some proxies, such as burnt bone and lithics, are more durable than charcoal and ash, and will be better preserved. The dawn of fire use is an important issue, much discussed in popular archaeological literature, and as such, needs to be clarified by further data – each early fire-using site is more important for publication than non-fire-using sites.

Different researchers have different bars for accepting evidence for deliberate fire use. Some over-interpret natural data, interpreting natural fire as anthropogenic. For instance, burnt clay found at Chesowanja (Gowlett et al. 1981, 2023, Gowlett 2016) provides no greater evidence for fire than burnt sediment at the much later Bezez Cave (Copeland 1978). However, the former is much more publicised because of its early date and novelty. This is because Neanderthals definitively used fire, evidenced by other proxies on other sites, and so for a “fire-using species”, one proxy is considered sufficient evidence. As a single proxy, the evidence is no stronger at Chesowanja than here. Other researchers require far *greater* fire evidence than would be required at more modern sites. For instance, at Cantalouette, a Neanderthal open-air site, burnt lithics were the only evidence of fire (Clark 2015). These were described as burnt in domestic fires, as we know from many sources that Neanderthals used domestic fire, so it being burnt thus is plausible. Similarly, burnt sediment in AMH hunter-gatherer sites are described as combustion feature, as we know AMH use fire. But oxidised sediments at Koobi Fora, providing equal if not greater evidences of controlled fire, have also been interpreted as natural stumps of bush fires (Isaac 1977). Found in FxJj 20 Main, FxJj 20 East and FxJj 20 AB sites, these sediments are clustered, highly localised patches, however without any thermally-altered lithics or bones (Bellomo 1994). 2500 lithics and 3000 bones were found very nearby in close stratigraphic association, clustered around these areas in distinct drop-zones (Hlubik 2013). If these represent hominin fires, they were not used for anything other than immediate heat and light (Ibid).

For identifying emerging technologies, the evidence has to be greater than for later, less-contentious technologies. But this goes contra to how technological development happens; the first hominin fires, even if completely ignited, fuelled and controlled by them, would be short-lived and ephemeral, occurring in few sites, and most likely lost from due to their great antiquity. A similar issue affects uncertain Neanderthal burials, whose proxies (grave cuts, grave goods, cairns, skeletal condition, limb positioning etc.) must be manyfold to be accepted. Many “burials” (e.g. Regourdou 1 - Vandermeersch 1995) have been described as natural, not anthropogenic processes (e.g. Dibble et al. 2015, Gargett 1989, Pelletier et al. 2017 and Sommer 1999). These papers do not always follow the simplest inferences; Gargett imagines infilling of the La Ferrassie by sediment slumping, despite its sharp profile (Bricker, comments on Gargett 1989). Proposed “burial” criteria are too strict; as “the act need not be complicated by the inclusion of grave goods; disposal of a corpse in a pit (even a natural one) and covering it with dirt or rocks constitutes a mortuary rite” (Grayer and Montet-White, comments on Gargett 1989, p.180). Likewise, by making criteria for “fire use” too strict, many valid examples are consigned to natural causes.

III: Later Fire Use.

In contrast to contested earlier fire-using sites, fire use in later sites is increasingly clear, due to being found in many more sites with increased hominin presence in each. Gesher Benot Ya’aqov (c.800ka BP) is among the first locations of proper, controlled fire, containing concentrated burnt flints in well-defined ‘phantom hearths’ (Alperson-Afil 2008). Enough heat was created to burn flint, without uniformly burning all sediments or leaving other traces indicating natural fire. In China, the similarly-dated Zhoukoudian site, home of the Peking Man (*H. erectus*), contains extensive fire evidence, including charcoal, burnt nuts, burnt lithics and eggshell fragments (Attwell et al. 2015, Gao et al. 2017). However, it completely lacks hearths, and the fire may be natural and unrelated to the hominin remains (Binford and Ho 1985, Binford and Stone 1986, Boaz et al. 2004, Goldberg et al. 2001, James 1989, Weiner et al. 1998, all in Gao et al. 2017). Beeches Pit (UK), c.400ka BP, contains refitting burnt flint, whose clustered nature does not suggest natural fires (Gowlett 2006). Around this time, the site of Schoningen produced hearths, burnt wood and burnt lithics (Thieme 2005) – although Stahlschmidt et al. (2015) debate their intentionality based on poor excavation details, with low wood reflective values suggesting humidification rather than carbonization. Clustered burnt artefacts in discrete areas strongly suggests deliberate fire use, as opposed to uniform spreads suggesting natural fire (Bentsen 2014). Subsequently, MIS 9/10 shows a sudden hiatus in fire, before MIS 8 sites resume fire use (Sandgathe 2017). These include Terra Amata, Grotte du Lazaret, Bilzinsleben, Menez Dregan and Vertesszollos (all Gowlett 2006). Whilst glaciation destroyed many MIS 9/10 sites, and especially more fragile hearth elements, nonetheless it should not have obscured all evidence, particularly burnt lithics. Sandgathe (2017) notes correlations between fire and warm periods, suggesting continued reliance on natural fire. These fire-using sites, increasing gradually from c.400ka BP (Gowlett 2006), interestingly correlate with above-mentioned increase in overall fire visible in deep-sea cores. Whether increased hominin fire use caused this change, or whether increased natural fires allowed more hominin fires to be created is unclear, although the latter theory is more plausible. Palaeolithic hominin fire, as a proportion of the whole, would be insufficient to cause major climatic shifts. Increases in natural fire however not only provided more burning material for igniting hearths with, but also more fire to be seen and incorporated independently as a novel technology.

In Africa, Wonderwerk Cave, at c.1Ma, has burned bone and plants in distinguishable clusters (Attwell et al. 2015), as does Swartkrans at c.500ka BP (Gowlett 2016). Kalambo Falls (Zambia) has burnt wooden artefacts, charcoal, reddened sediments and carbonised grass stems (Ibid, Barham and Kleindienst 2023, James 1989). By the Middle Stone Age (MSA, c.280-50ka BP), 34 African sites have extensive fire evidence, including charcoal at 26, burnt bone at 12, burnt lithics at 9, burnt seashells at 6 and burnt eggshell at 3 (Bentsen 2014). Crucially, 24 sites have discrete hearths, over half of these with burnt substrata (Ibid). These fire-using MSA sites are common enough that we consider *H. sapiens* to have always been habitual fire users. The question remains, however, whether *H. neanderthalensis,* from a similar period, did likewise. Certain non-*Homo sapiens* species like *Homo heidelbergensis* certainly used fire in Africa, including in the aptly-named Cave of Hearths (Pearson and Grine 1997).

IV: Neanderthal Fire Use.

Despite earlier fire use by other hominins, Neanderthal fire practices are hotly contested. The question is not whether *any* Neanderthals used fire, as that is unquestionable, but whether this activity was regular, or rather, whether Neanderthals were *obligate* fire users. For an activity to become obligate to a species, that species must evolve, morphologically or behaviourally, so that a lack of that activity causes serious species unfitness, and possible extinction. A classic example for modern humans is clothing. Whilst *H. sapiens* survive naked in warmer countries, in colder climates we risk serious hypothermia, unlike animals with fur or extensive subcutaneous fat reserves. Thus in northern climates we are obligate clothes-wearers. However, our lineage had already lost its hair by the Australopithecine era (David-Barrett and Dunbar 2016), long pre-clothing. Consequently, clothes-wearing did not drive evolutionary change, but it did facilitate range expansion without further physical evolutionary adaptations. Clothes manufacture through a complex chaine operatoire did already require a certain degree of intelligence however (although see counter-claims by Collard et al. 2016).

Modern industrialised human societies depend on fire use. Many material transformations underpinning our society depend on fire (cooking, melting, smelting, welding etc.). Without fire we could not create environments to sustain our current population densities, which particularly depend on combustion to drive machinery, transport etc. Whilst modern non-industrial lifestyles amply demonstrate that fire-driven mechanisation is not essential for non-industrial human survival, nonetheless it is essential to sustain current industrial population levels. Furthermore, humans use fire to directly transform landscapes (e.g. burning down forests to create farmland). Secondly, fire is used alongside clothing and habitation insulation to create warm living spaces in cold climates, and is vital for continued range expansions. Thirdly, and most importantly, modern humans rely on cooking (Carmody and Wrangham 2009b). The Expensive Tissue Hypothesis posits that energetically-demanding brain tissue development came at evolutionary costs of reducing other energetically-demanding body tissues, namely the gut (Aiello and Wheeler 1995). *H. sapiens* had smaller guts than their ancestors, and couldn't easily digest low-quality foods. Large energy-demanding brains necessitated a switch to higher-quality diets, or an improvement to existing diets. The former would require longer foraging times or new strategies; cooking supplied the latter however. Although primarily discussed in Chapter Four, cooking increases food's calorific value through breaking down molecules in a form of external digestion, meaning the body expends less energy breaking it down (Wrangham et al. 1999). It also sometimes destroys molecular barriers, allowing larger surface areas of swallowed food to be accessed for digestion (Ibid). Humans can survive on less cooked food than raw food, so less can be gathered, shortening foraging hours and freeing more time for other activities. However, see Schrempp (2011) for an anthropological critique of Wrangham's approach. Over time, further morphological changes meant that humans could no longer survive on raw diets. Since cooked food is much tenderer than raw food, human molar size reduction from c.100ka BP (Wrangham and Conklin-Brittain 2003) and reduced masticatory muscle power (the Anterior Dental Loading Hypothesis – Clement et al. 2012, Smith 1983) meant that humans could no longer chew raw food effectively. Further gut reductions meant that even fewer calories could be acquired from raw food. Consequently nowadays, every modern human society uses cooked food, and those deprived of it suffer. Studies on modern "raw-foodists" (people eating exclusively raw diets for supposed health benefits) found chronic malnourishment amongst these groups, despite eating similar quantities of identical food groups as the rest of society (Koebnick et al. 1999).

Whilst industrialised humans are obligate fire-users, there is less evidence that Neanderthals were. Neanderthals, lacking industrial settings, had fewer uses for fire than we do; they had no combustion-dependent machinery, or metals to fashion. Unlike modern hunter-gatherers, there is no evidence that Neanderthals used fire to create optimal foraging environments to sustain higher population densities (Daniau et al. 2010). The only example of this might be a dependence on hafted technology for hunting large game, which can use heat to melt hafting adhesives, or non-thermal binding methods. A main obligation may have been through the Expensive Tissue Hypothesis. However, whilst Neanderthals had brains as large as *H. sapiens* (Kochiyama et al. 2018), concurrent gut size reduction is less evidenced. Whilst probably having smaller guts than *Australopithecus*, Neanderthals were notably barrel-chested and stocky, with larger bodies. Their gut bacteria were comparable to ours, and they could have digested similar foods (Rampelli et al. 2021). Furthermore, their teeth are notably larger than *H. sapiens,* and they had correspondingly large jaws and masticatory power (Clement et al. 2012, Smith 1983). We do not know whether Neanderthals could have survived on fully raw diets; whilst some materials may have been eaten raw or partially-fermented (Buck and Stringer 2014, Speth 2017), with both large brains and large guts, their metabolic rate and need for high-quality foods would have been even greater than AMH. Whilst many believe they satisfied this through large-scale consumption of high-protein meat sources (Richards et al. 2008), fire and cooking food would have helped their energetic requirements. Whether or not Neanderthals were *obligate* fire users from morphological or behavioural perspectives (Chazan 2017), fire would certainly have been a valuable tool. *Obligacy* and *stability* are different; Neanderthals could have survived easy climatic periods in the same way that some AMH survive without fire (see p.311), but in times of resource stress, modelling predicts that fireless Neanderthals would have suffered and potentially gone extinct (Goldfield et al. 2018).

Neanderthals strongly evidence fire use, at both a species and a regional level. Fire evidence has been found in throughout their European and Near Eastern range, sometimes with very extensive hearth remains (e.g. Abric Romani and Kebara - Albert et al. 2012, Carrancho et al. 2016). Middle Palaeolithic fire is much more common than in the Lower Palaeolithic, although this may partly be a taphonomic bias of many Middle Palaeolithic sites being protected in caves, and Lower Palaeolithic sites generally being open-air (Stahlschmidt et al. 2015). This has preferentially preserved Neanderthal hearths; however, potentially confusing wildfires are more likely to occur in Lower Palaeolithic open-air sites therefore, increasing their overall fire record. There are many fireless Neanderthal sites as well; see Chapter Three, p.86 for details. By contrast, Upper Palaeolithic sites evidence far greater fire use than Middle Palaeolithic ones (Murphree and Aldeias 2022). Studying fire *frequency* requires detailed multi-proxy study of all levels of a site; this has been undertaken at Roc de Marsal and Pech de l'Aze IV, France (Aldeais et al. 2012, Dibble et al. 2017, Goldberg et al. 2012, Sandgathe et al. 2011). These valuable papers found that fire was only used in certain levels of each site. Studying the prevalence of fire within a stratum is difficult, as level of fires required to create given amounts of archaeological fire proxies are unknown, and differs between different sediments and taphonomic processes. However, intra-level comparisons within single sites are valuable; despite potential sedimentary and taphonomic differences between levels, these can be assumed to be sufficiently similar for useful comparison.

Sandgathe and colleagues conclude that whilst Neanderthals knew how to use fire, they could not *create* it (Ibid). This distinction is important. This inference is based on correlated warm climatic periods and increased Neanderthal fire use at this site. Warmer times would have more vegetation growing for fuel and more lightning strikes, and thus more exploitable wildfires (Ibid). This expedient fire use could explain both Neanderthal fire and their evolutionary morphology; Neanderthals used fire when naturally available, curating it into anthropogenic contexts and keeping it alive by providing fuel; however this was not frequent or reliable enough for regular cooking, which may explain why Neanderthals retain large teeth, masticatory powers and gut size, unlike AMH. Alternatively, large teeth could just be a retained trait rather than being selected for. To these authors, Neanderthals as a species understood and used fire when possible, but their lack of fire-starting technologies proved an insurmountable barrier to their incorporating it into regular behavioural repertoires.

However, whilst satisfactorily explaining odd solitary fires in mostly-fireless sites, such as Wallertheim (Clark 2015), this explanation is implausible for exceptional sites like Abric Romani, Kebara and Shanidar, where hearths are consistently present over long sedimentary sequences (Albert et al. 2012). In these instances, Neanderthals may either have carefully kept one (natural) fire alight over exceptionally long periods, which seems unlikely given the transhumant nature of these people. Alternatively, they must have possessed some fire-starting techniques. Sorensen and colleagues (2018) have demonstrated how easily striking Mousterian bifaces against pyrite creates sparks, and argue that biface use-wear patterns support their use for this function. However, whilst use-wear patterns are consistent with this interpretation, they could be consistent with other pounding-related functions (e.g. crushing plants for food processing). Just because Neanderthals had the potential for certain behaviours, does not mean that they did them. Another common modern fire-starting method is wood-on-wood cord-based friction (Stahlschmidt et al. 2015). All components of this are organic and would not have survived, and direct evidence of this only survives from the Upper

Palaeolithic onwards (Ibid). Recent finds of constructed twisted fibre cords at Abri du Maras, France (Hardy et al. 2020) suggests that Neanderthals could construct rope and knots, potentially for fire-starting. However, once again this is no guarantee that they did so.

The crucial question then is, how prevalent was fire use by Neanderthals, from spatio-temporal perspectives? Many sites report fire, particularly clustered in the Iberian Peninsula (Abric Romani, El Salt, El Esquilleu etc.) and the Near East (Kebara, Amud). However, sites with extensive fire use are better studied; I have noted over 30 papers on Abric Romani's fires, over 20 on that of Kebara, 16 on Amud etc. Others with minimal fire use have largely been ignored, except for original, often obscure site reports, and sometimes separate reports on fauna or lithics but rarely on the fires themselves. Thus sites with abundant fire use and other artefacts become even better-documented, with more proxies for fire employed, and those seemingly without are ignored. This is an important recording bias. Reports without obvious fire don't necessarily negate its use, just that it was not noted, either due to original infrequent use or subsequent taphonomic processes destroying the evidence. To address these problems, I look at each criterion used to determine fire use; hearths, and their constituent components of rubified sediment, charcoal, ash, burnt lithics and burnt bone.

IV.I: Hearths and Rubified Sediment.

The most ubiquitous sign of man-made fire are hearths, and almost all anthropogenic fire was originally contained in such structures; the exceptions being torches and deliberately-fired wild landscapes, neither of which Neanderthals were known to do. To define a "hearth" is complicated. Its placement is designed to reduce the flame's exposure to wind or rain. Digging even shallow fire-pits negates wind-chill on the flames, allowing higher temperatures to be attained whilst using less fuel. These are common in Upper Palaeolithic and subsequent sites. Whilst extremely rare among Neanderthals, fire-pits exist at Abric Romani (Vaquero et al. 2004), Kebara (Albert 2000, Meignen et al. 2007) and La Roca dels Bous (Martinez-Moreno et al. 2004). However, Meignen et al. (2007) notes from observing modern Hadza people that scooping ashes from long-term hearths form unintentional concave depressions over time. Thus these apparent pits may just result from maintenance, rather than active preparation – they still demonstrate hearth maintenance and reuse, important factors as mentioned below.

Another aspect of “planned hearths” is ringing them with stones; common today, but only noted twice for Neanderthals, at Bison Cave, France (Courty 2017) and Grotta Maggiore di San Bernardino, Italy (Lopez-Garcia et al. 2017). Both this and pit-digging provide wind shelter; however, they also serve an important function, viz. a visible division of “hearth” and “non-hearth”. These constrain, both physically and conceptually, fire use to within this area, and social, manufacturing and waste spaces to be outside it. Generally speaking, Neanderthal sites are “unstructured”, without discrete activity areas; there are notable exceptions however. In Bruniquel Cave (France) and Grotta Grande di Scario (Italy), Neanderthals used broken stalagmites to form boundaries, or as bases for fires (Jaubert et al. 2016, Ronchitelli et al. 2011). For creating individual or small-group zones, dwellings of mammoth bone were erected at Molodova I, Ukraine (Demay et al. 2012) and Chatelperron, France (Lacaille 1947). Occasional Neanderthals understood structured space, occasionally extending this to their hearths as well. They did not however have flues for removing smoke. Situating fires at cave entrances partially mitigated this, but smoke from fires further in would have caused decreased vision, respiratory irritation and longer-term cancers. This latter may have minimally impacted Neanderthals dying earlier through other causes such as hunting injuries however (Berger and Trinkaus 1995, Nakahashi 2017). Smoke build-up may have also affected a fire’s ability to burn at full heat/brightness. Consequently, smoke-free fuelwoods would have been especially valuable.

Once constructed, burning activities commence, and this can cause rubefaction (reddening) of sediments beneath the hearth – see Figure 1 below for rubified sediment at Shanidar Cave, Iraq. This change is due to increasing proportions of iron-bearing minerals; goethite changes into haematite, and limonite to maghaematite through water loss (Moody 1976, Salomon et al. 2015, Schindler et al. 1982, pp.528-529). Different sediments have different iron contents, affecting degrees of rubefaction expected (Sergant et al. 2006). Different sediments transmit heat to varying degrees (Carrancho et al. 2014); heat transfer also strongly depends on soil water content (Bachmann et al. 2001) and air-filled porosity (Ochsner et al. 2001, p.1646). Carrancho and colleagues (2014) found that 3cm-deep thermocouples did not register above 120°C, even though the fire mere centimetres above was 700°C; Clemente-Conte (1997) found temperatures of only 60-70°C 3-5cm beneath fires. However, Werts and Jahren (2007) found much hotter sediment temperatures; 1cm beneath a fire was 700°C, 2cm was 400-500°C, 3cm was 300-400°C, and 4cm was 150°C. When examining magnetic effects of heat on sediment, no changes were noted 2cm beneath the fire, and few below 1cm (Herries and Fisher 2010).

Figure 2.1: Rubified sediment from Shanidar Cave, Iraq. Photograph: Graeme Barker, 2023.

Thus rubefaction depends on temperature, which itself depends on hearth construction and fuels used. Hot-burning fires might produce more reddened sediment, dependent on substrate variables; if AMH fires were hotter, they might create more rubified sediment than Neanderthal ones. Another important factor however is duplication, and how many times a particular area was fired. Single fires might leave minimal burnt sediment beneath, but multiple superimposed fires over time may produce much more. How often then did Neanderthals reuse single spots for hearths – and how is this detectable? It would be a cyclical argument to assume that rubefaction evidences reusing hearth spots, and to subsequently assume that reusing hearth spots causes more rubefaction. More notable are spatial evidences of reuse; virtually-overlapping but partially-discrete patches of rubefaction as at Vanguard Cave, Gibraltar (Meignen et al. 2007). Temporal evidence of reuse, with multiple layers vertically visible in section, are noted in Shanidar (pers. obvs.). Finally, cleaning activities evidences hearth reuse; if a spot is reused, ashes from past fires must be removed and dumped elsewhere on site to create pseudo-hearths, or 'ash dumps', pit features filled with homogenous almost-white ash without any charcoal. Ash dumps are found at La Roca dels Bous, France (Martinez-Moreno et al. 2004), Kebara, Israel (Meignen et al. 2007) and possibly De Nadale Cave, Italy (Livraghi et al. 2019), suggesting that, occasionally, Neanderthals tended to and reused hearth areas.

However, reusing versus making new hearth areas does not evidence modern behaviours, or experience with fire technology, as modern human groups do both. Ethnographically, the Pinai of New Guinea remake hearths in different areas each time they use a rockshelter, whilst the nearby Melpa reuse the same spot each time (Clark 2015). One here does not have a *more advanced* use of fire than the other, or that one or the other is more *cognitively modern*. These two methods make different archaeological features; the Melpa, as with the Kebaran Neanderthals, by exclusively burning in one spot, create very strong unmissable fire features in limited areas. If another part of the cave is excavated, fire may well be missed. The Pinai, as with many other Neanderthal groups, spread their fire around, creating weaker fire signatures throughout the cave, detectable in more test pits. Charcoal and micromorphological procedures strongly impact whether fire is found, and, naturally, larger samples increase the probability of detecting fire. Uniform sampling protocols would enable better inter-site comparisons, but these criteria are vague and not yet agreed upon.

Figure 2.2: Shanidar Cave, Section 111.1. The upper dark charcoal-rich layers do not represent distinct hearth events but rather a palimpsest. Palimpsests are living surfaces where individual events are blurred, overlapped and slowly buried over time rather than representing discrete events. Photograph and diagnosis: Graeme Barker.

Complete hearths usually have a rubified basal layer, then charcoal, then ash (Meignen et al. 2007). Other elements like lithics and bones can be found at various layers in this, depending on if they were present pre-fire, added during it, or after it was out. In disturbed contexts, all of these are scattered randomly throughout the sediment – see Figure 2 above for an example at Shanidar. Meignen et al. (2007) takes single charcoal-ash couplets to represent single combustion events, but doesn't mention whether two-hour fires produce different signatures to ones burning for weeks or months. But it is to other elements of the hearth, charcoal and ash, that we must now turn our attention.

IV.II: Charcoal.

Charcoal is the byproduct of incomplete combustion of woody substances in reducing conditions. Pristine charcoal almost perfectly resembles original cells of the fuelwood it came from, albeit with varying degrees of shrinkage (Deforce et al. 2013, McGinnes et al. 1971, Sun et al. 2022). These perfect specimens can determine which genera were burnt, and in what proportions (Chapter Five, p.146-149). Degraded charcoal forms amorphous, molten balls, unrecognisable through vitrification (Marguerie and Hunot 2007, McParland et al. 2010). Charcoal is 60-90% high-condensed, aromatic carbon (Eckmeier et al. 2007a,b); incompletely pyrolyzed charcoal also contains cellulose, hemicellulose and lignin (Braadbaart and Poole 2008). It is one of the most easily recognised by-products of fire use, and has been found in over 120 Neanderthal sites (see Chapter Three). Unlike burnt sediment, it is often found outside hearths, or where they have been destroyed. Charcoal is a well-known pyrolysis by-product; its genera-specific cell features makes it invaluable in palaeoenvironmental reconstruction. It is often sought out, and is commonly reported when present.

Not only anthropogenic hearths create charcoal; wildfires also create great quantities of very transportable charcoal. During fires, smoke instantly carries away 2% of the charcoal (Wu et al. 2019); larger particles travel hundred of metres to a few kilometres (Ohlson and Tryterud 2000, Tinner et al. 2006) – microscopic ones travel hundreds of kilometres (Tinner et al. 1998). Whilst it is unlikely that macroscopic charcoals used to determine the fuelwoods burnt, and surrounding environment, are from outside the site, natural events could contribute microscopic charcoal creating "charcoal-rich layers". This problem is compounded in open-air Neanderthal sites where aeolian catchment areas are much larger. Neanderthal cave and rockshelter sites have narrower entrances than open-air sites; those in karstic areas may have fewer trees (Daujeard et al. 2016, Zhao et al. 2020), and be likely to suffer on this account. Charcoal can be fluvially transported for days or weeks before sinking (Scott 2010). Certain Middle Palaeolithic riverine sites, most notably Nahal Manahayeem Outlet, exhibit fluvial sorting and redeposition, potentially including fluvially-deposited charcoal. Cave and rockshelter sites are above river valleys, and the water that they receive is often from above the treeline, but they do suffer from water movement from within the karstic system. Finally, charcoal is moved and redeposited through bioturbation (trampling, burrowing) or under erosion; on <1% slopes, 7-55% of charcoal from recent fires erodes by rainfall alone (Rumpel et al. 2009). Again, this is more likely to occur outside than inside caves.

However, these processes, whilst also introducing charcoal to sites, may also remove it. Open-air sites are theoretically much more prone to taphonomic processes removing fire evidence than caves. For charcoal in particular, several degradation processes occur. Whilst fracturing and splitting are problematic for genera identification (fragments <2mm are usually unidentifiable), this does not reduce the charcoal mass, only making it smaller and more prone to subsequent transport. Other processes actively destroy charcoal, breaking it down into molecular components; these processes include fungal attack (Allue et al. 2009), microbial decomposition (Eckmeier et al. 2007a), uptake of carbon by plants, oxidation over time (Cohen-Ofri et al. 2006) and environmental pH (acidic environments preserve charcoal better – Braadbaart et al. 2009). Whilst some of these factors depend on soil texture, taphonomy and conditions, many depend on living organisms (fungal, microbial or floral) in the soil. Cave sites are again more likely to be sterile, and their charcoal more likely to survive as fire evidence. Poorly-preserved charcoal and other burnt materials are confusable with manganese (Lopez-Gonzalez et al. 2006). This is particularly important in early fire-using sites, where the overall presence of fire may be confused if “charcoal” is actually minerals.

Finally, many Middle Palaeolithic sites also contain Upper Palaeolithic (AMH) layers, and some have transitional layers (Chatelperronian, Uluzzian etc.), which may contained Neanderthal or AMH material, or both. If AMH used fire and Neanderthals didn’t, or did so only occasionally, Middle Palaeolithic layers may be charcoal-free whilst Upper Palaeolithic layers are charcoal-rich. However, vertical charcoal movement through water percolation, burrowing animals or other bioturbation confuses this. Worms and growing root systems move charcoal by up to 5mm a year (Bal et al. 2010, Stuart and Walker 2017, Wood and Johnson 1978). Sediment textures affect this, as lighter soils promote faster movement (Foereid et al. 2011). Thus ‘Middle Palaeolithic’ charcoal may originate from Upper Palaeolithic contexts. This issue is once again more likely to affect open-air Neanderthal sites than caves, as dark caves limit plant growth, and low organic contents of cave sediments deter worms and other burrowing animals. This does have exceptions though; Shanidar Cave sediments were notably disturbed by burrowing bees or jirds (Hunt et al. 2023, Sommer 1999).

IV.III: Ash.

Ash is the other primary combustion by-product of woody substances; a greyish-white powdery alkali, composed chiefly of needle-shaped nanostructured calcium- and potassium-oxides (Kabukcu 2015). Due to its homogeneity, the genus that created it cannot be identified, except for *Pinus* (Mentzer, pers. comms.). Phytoliths (small silicate bodies) can also be found in ashes. Whereas charcoal represents incomplete combustion in reducing conditions, ash forms in more complete, oxidising conditions, although certain wood genera produce more ash than others (Glaser et al. 2002). Thus, charcoal and ash frequently anticorrelate; in deoxygenated fires, more charcoal is created at the expense of ash, and with abundant oxygen, ash is created and little charcoal. In practice however, hearths' interiors will almost always be reducing environments and produce charcoal, whilst exteriors are open to oxygen and produce ash. This explains the layering effects of charcoal and ash on many sites. Charcoal-producing experiments frequently replicate reducing atmospheres by covering wood in sand or otherwise limiting the oxygen; however open-fire experiments create less charcoal and more ash (Umbanhowar and McGrath 1998). Whereas ash creates paler stratigraphies when present, its ephemeral nature means that it is underreported, except where publications directly discuss fire use.

Ash, being very diffuse, is prone to fluvial transport away from fire features, dissolving in water as in Amalda I Cave (Sanchez-Romero et al. 2020) and Grotta dei Santi (Spagnolo et al. 2020b). It is also less obvious than charcoal, unless concentrated, and rarely forms discrete easily-recognisable lumps. However occasionally, light water input from speleothems onto fire features causes concretion effects, cementing ash into hard lumps in-situ, preventing further loss. This has occurred in Amud Cave (Alperson-Afil and Hovers 2005) and Shanidar Cave (pers. obvs.). In one instance, at Qafzeh Cave, ashes cemented themselves in and around lumps of burnt ochre (Hovers et al. 2003). Ash can also be preserved in discrete dumping areas resulting from hearth maintenance activities; these are preserved at La Roca dels Bous, Kebara and De Nadale Cave (see Chapter Three).

Figure 2.3: In-situ ash layers in Shanidar Cave, Section 14.1. Photograph: Graeme Barker.

However, ash is alkaline and charcoal is acidic. In situ, these components can react with each other, destroying both (Huisman et al. 2012). Soil pH affects preservation of both components, and again anticorrelates, as if acidic, charcoal is preserved, whereas ash is preserved in alkaline environments. Substrate consistencies also matter, as porous sands and gravels facilitate water percolation, dissolving the ash, whilst clay excludes water (Mentzer 2011). Open-air sites may preserve less ash than cave sites, due to a greater potential for sediment transport. However, whilst charcoal is recognisable in small quantities diffused throughout sediments, and may be brought into sites from wildfires, ash must remain in significant quantities to be noticed; this increases the chance that sedimentary ash layers formed in-situ from anthropogenic activities. See Figure 3 above for an example in Shanidar Cave. The important caveat is volcanic activity, which produces sufficient ash to mimic burnt layers; as at Crvena Stijena (Bakovic et al. 2009) and Oscuruscuito Rockshelter (Spagnolo et al. 2016). However, this occurs only infrequently.

Rubefied sediment, charcoal and ash are three integral, primary aspects of a hearth. Whilst rubified sediment is almost exclusively found in-situ, charcoal and ash are frequently distributed in sediments, creating ‘burnt layers’ testifying to Neanderthals fire use but without disclosing the number or nature of the hearths. Whilst hearths can occur without rubified sediments, all fires, at least initially, produced either charcoal or ash or both, although these may subsequently have been lost. In some situations however, other objects are burned by the fire’s heat, and their groupings indicate hearths even where other evidences have been lost. I refer here to burnt bones and burnt lithics.

IV.IV: Heat-Altered Lithics and Stones.

Lithic debitage scatters from knapping activities are an important part of prehistoric sites. Lithics have great heating potential, either in hearths (deliberately or accidentally left there), or in underlying substrates, altered as sediments conduct heat to them. These can of course be unworked pieces, tools or flake by-products of tool manufacture. However, except where ring-hearths survive, heated unworked stones are ignored in publications, as they focus on taphonomies of *worked* stone. This more closely ties modifications to anthropogenic causes; burnt tools are more likely to have been deliberately heat-treated during manufacture, or discarded in anthropogenic contexts and burnt by anthropogenic fires, rather than having been burnt in wildfires.

However, “natural” stones should still be noted as evidence of fire use, if not of intentional heat-modification. Unworked stones are less likely to have been moved by Neanderthals, not heated at one location and deposited at another unlike finished tools. Furthermore, if worked stone originally came from naturally burnt rock outcrops, deliberately selected as more easily minable than unburned ones, then the fire may not have been anthropogenic at all. Looking at burnt unworked (and low-quality, unworkable) stone helps with this issue.

An important and common, though not consistent, heating signature is a rubefaction (reddening) of outer surfaces of lithics (Delagnes et al. 2016, Frick et al. 2012), under the same principles as that of sediment rubefaction mentioned above. Organic materials carbonising (e.g. lipids) cause surface darkening (Rottlander 1989). Without haematite present, surfaces whiten or turn grey/black when heated (Bentsen and Wurz 2019, Nadel 1989). Both rubefaction (Delage and Sunseri 2004, Driscoll and Menuge 2011) and surface whitening/greying/darkening (Ahler 1983, Clemente-Conte 1997, Kiers 2018) are standard traditional ways of noting lithic heating. Rubefaction generally occurs at lower temperatures; 200-400°C for cherts (Edwards and Edwards 1990, Zhou et al. 2013), with whitening occurring at 300-600°C (Schmidt 2014) and darkening at 250-425°C for chert (Ahler 1983), and 300-800°C for caliche (Lintz 1989). However, reddening is inconsistent, and dependent on goethite patches. Heated quartz generally whitens with pink patches (Driscoll and Menuge 2011). Given rubefaction depends on iron-bearing content in the rocks, those with under 1100 iron parts per million don’t redden, but whiten or darken (Purdy and Brooks 1971). These colour changes are also weak and prone to fading over many millennia (Canti and Linford 2000), only affecting outer surfaces, and are lost if the rock is subsequently knapped and reduced (Patterson 1995). All these issues however concern loss of evidence and do not affect validities of colour changes when detected. However, these colours are by no means standardised, and crucially can remain within natural unheated ranges of that lithic type (Lavin 1983, Rowney and White 1997). This causes confusion as to whether reddish lithics were heated, or from naturally rubified sources, leading to false assumptions (Melcher and Zimmerman 1977, p.1361, Sunseri and Delage 2016). It is crucial to have natural geological reference samples of all lithic sources.

Another diagnostic of past heating is lustre, a waxy/greasy surface on flake scars and exposed surfaces. This reliably indicates past heating (Collins and Fenwick 1974, p.137, Monik et al. 2019). Lustre was once thought to be due to crystalline pores being filled with gas rather than liquid, giving it higher reflection coefficients – however this is now thought to be due to heating changing flint's fracture patterns. It becomes more glass-like with smoother fracture planes reflecting more light, and defining any surficial crystal facets more smoothly (Fiers et al. 2021, Schindler et al. 1982, Schmidt et al. 2019). In addition, heating increases the quantity of anatase (TiO_2) in chert, which has a high refractive index (Delagnes et al. 2016). This happens at various temperatures, with changes noted from 150°C to 550°C (Flenniken and Garrison 1975, Joyce 1985). Again, heating does not always cause lustre (Collins 1973, Domanski and Webb 2007, Frick et al. 2012), and taphonomic or anthropogenic factors including bioturbation, weathering or further lithic reduction can remove it (Price et al. 1982, Rick and Chappell 1983). Furthermore, degrees of lustre vary depending on anatase concentrations (Bass 2009). These are all loss/absence issues, but repeated microwear polish, patination or weathering may also cause lustre (Hess and Riede 2022, Melcher and Zimmerman 1977). Furthermore, lustre is only present on *post*-annealment scars (Mandeville 1973, Monik et al. 2019, Moody 1976, Schmidt et al. 2017), where upper faces of flint remain matte and lower ones have lustre (Delage and Sunseri 2004). Flints buried beneath Neanderthal fires and not subsequently reduced would not show lustre; the lithics would have to be split to reveal it, destroying them.

Electron Spin Resonance (ESR) can also detect heated lithics. Heating causes trace elements (manganese and organic elements) to move into new energetic levels (Robins et al. 1981). Signal intensities change as the number of E' centres (paramagnetic defects in quartz with an electron at an oxygen vacancy) increase at 300°C, where oxygen vacancies with two electrons are converted into new E’ centres (Toyoda et al. 1993). This is noticeable, as the standard narrow readily-saturated line at g=2.0017 is lost at 400°C, and a new line emerges at g=2.0035 (Robins et al. 1981). Whilst ESR is non-destructive, it misses low-level heating below 300°C (Dunnel et al. 1994); however this is an ‘absence’ rather than a false-positive issue, and thus would be suitable for addressing this question.

Another compelling piece of evidence is tempering residue on lithics; black organic wood tar produced by dry distillation of plant matter in fires, indicating direct contact with embers (Delagnes et al. 2016). Plant exudations vaporize, and condense on lithic surfaces. This gas cannot penetrate sediments, so only forms on surface stones (Schmidt et al. 2017), limiting this substance in Neanderthal records as many heated stones would be underground. This substance also only forms under certain circumstances (e.g. deadwood is insufficiently moist for this procedure – Ibid). Tempering residue can superficially be confused with other hafting tars (e.g. those on Neanderthal tools at Umm el Tlel – Boeda et al. 2008a). In the latter instance, the stones themselves were not necessarily heated.

The most common and easily-noted feature of heated lithics is structural damage, either internal damage (fissures, fractures etc.), or surface damage (potlidding/thermal bubbles, scaling, crazing). Such unintentional over-heating damage is often neglected by authors on intentional heat-treatment. Skilled heat-treaters heat stones to precise temperatures, giving desired structural changes without thermal damage. However, this thermal damage often provides usefully unequivocal evidence of uncontrolled firing, such as from Neanderthal fires.

These changes are partially caused by the same mechanisms making heated lithics desirable. These are mostly outlined in Chapter Four, but include hydrolytic weakening of single quartz crystals (Blacic and Christie 1984, Roque-Rosell et al. 2011) and easier fracturing due to water loss (Thiel 1972, Schmidt 2014). In addition, at higher temperatures water vapour escaping from pores, or created in reactions within rocks themselves, is trapped and cause fractures. Consequently, wetter and larger stones fracture more easily, as more water vapour has longer distances to escape from (Schmidt et al. 2012, Schmidt 2014). In addition, at 500-600°C, various minerals (including dolomite, anterite, siderite, magnetite, pyrrhite, pyrite, illite and kaolinite) decompose, volatise, oxidise or melt, increasing the size of the rock's inhomogenous defects (Sun et al. 2016). Heat-damage can be categorised into several discrete categories:

- Longitudinal fractures: splits through the longitudinal axis (Bustos-Perez and Preysler 2016).
- Marginal fractures: splits present in only one lateral margin (Ibid).
- Internal cracking: varying shapes, sizes and deepnesses, but all with distinguishable reticular shapes (Ibid).
- Scales: varied curvilinear macroscopic alterations; if scales further develop, they become thermal bubbles (Ibid).
- Thermal bubbles, or "pot lids": negatives of small flake detachments resulting from extreme scaling (Richter et al. 2011, Patterson 1995). These round-to-oval spalling patterns show a central point of departure (bulb), 1-60mm wide (Ibid), leaving smooth or rough thermally-glossed negatives (Bustos-Perez and Preysler 2016, Clemente Conte 1997).
- Fissures: microscopic surface fractures, either thin and shallow or wide and deep. They may be isolated; if they appear in groups, they become crazing.
- Crazing: net-like structures of "irregular hairline surface cracks" (Patterson 1995) on exposed surfaces. Crazing represents early mechanical failure (Frick et al. 2012).

These changes can be distinguished from mechanical forces by a lack of compressive force rings, or other diagnostic knapping features (Crabtree 1972, p.84), although it is difficult to distinguish longitudinal and marginal fractures from mechanical effects (Abdolahzadek et al. 2023, Patterson 1995). Many alterations are only surface-deep however, and can likewise be lost through further reduction (although this is not an issue with stones heated in sediments beneath hearths). Heat-fracturing is not as subject as some heat-effects to loss through patination and bioturbation. Temperatures vary between rock types, but generally chert starts to break from 100-550°C (Ahler 1983, Cooper 2002, Domanski and Webb 1992, Mraz 2019), chalcedony from 400-600°C (Ibid), jasper at c.530°C (Dillian 2017, Schindler et al. 1982 p.528), silcrete at 700-900°C (Mercierca and Hiscock 2008) and granite at 900°C+ (Simmons and Cooper 1978, Wang and Konietzky 2020). However, damage occurs at c.300/350°C for chert, depending on heating and cooling temperatures. Fast-heated cherts (350°C/h) shatter at 100°C, but not until 300°C if heated at 50°C/h (Domanski and Webb 1992) and some can withstand slow heating and cooling up to 600°C with minimal heat damage (Domanski et al. 1994). There is no formula for which damage type occurs at which temperature. Generally, with increasing temperature, scaling becomes potlidding, and fissures become crazing and eventually fracturing. This varies by unquantifiable amounts due to varying water contents, even within particular rock types, and likewise varies between outer cortices and the inside.

Heat-damaged lithics have been used as a proxy for controlled fire at Gesher Benot Ya'aqov, Israel, at 790ka BP (Goren-Inbar et al. 2004). In my opinion, heat damage, especially when combined with other methods, is an easy, visual, non-destructive identification method that whilst missing some heated items, does not give false positives. It must be noted that weathering and frost cause similar effects (Goksu and Wieser 1989, Lautidrou et al. 1986, Michel et al. 2019), but these are generally restricted to general fracturing rather than surface effects. However, like some other methods, it is still very subjective, depending on individual bias and researcher experience. Heat-damaged rocks are a frequent proxy for heating water for boiling food; the general lack of publications on heat-damaged unworked Middle Palaeolithic stones suggests that Neanderthals did not undertake this technology, although conversely, this assumption means that researchers have not looked out for burnt rocks in this context.

No one method detects fire 100% accurately (Olausson and Larson 1982, p.277); most are used only alongside other affirming methods (Purdy and Brooks 1971, Patterson 1984, Monik et al. 2017, 2021). Experiments, albeit on experimentally-heated chalcedony rather than chert, showed that only 45% of the pieces visually alter with heating (Joyce 1985). Although some results give false positives, a vast majority underrepresent the incidence of heating. These methods show the *minimum* number of lithics heated from the *minimum* number of fires.

When looking directly at the effects of distance from the fire on heat damage, cherts by the edges of fires will only be affected on those sides closest to heat, those 5cm beneath fires may show fracturing and localised crazing, those 15cm beneath sometimes lightly fracture, and those 20cm beneath are unaltered (Lawrence and Mudd 2015). More conservative estimates found no heat-damage on any buried pieces (Ortiz Nieto-Marquez and Baena Preysler 2015). These extremely valuable experiments demonstrate that 15cm is really the maximum distance to which any heat damage is observed, and that lithics must realistically be within burning fires to experience the full effects. Although temperatures beneath fires may cause rubefaction, or lustre, heat-damage depends on sudden temperature fluctuations, only occuring in or very shallowly beneath hearths. This may however cause potentially confusing issues if overlying Upper Palaeolithic fires burn lithics buried in underlying Middle Palaeolithic contexts. Careful stratigraphic recording, and noting the presence of "modern human" fires above burnt lithics in older contexts can address this issue.

This section shed lights on why so few traces of Neanderthal fire can be found from this method, and how they under-represent the whole. The methods giving false positives of fire are completely outweighed by instances of fire not imprinting onto lithics. Rubefaction and other colour changes are generally unreliable, although white calcination at higher temperatures (c.800°C) is more reliable. Lustre, whilst reliable, is only present in lithics subsequently knapped after exposure to fire. If Neanderthals were not deliberately heat-treating, there would be few cases of them expediently knapped burned stones gathered from hearths (Gould 1976, Lovick 1983). Thus superficially-examined lithics, without destructive modern sectioning, will not show lustre. Heat damage is the best diagnostic for uncontrolled heating, but is extremely buffered by sediment. Burnt lithics are frequently mentioned in reference to thermoluminescence (TL) dating, but rarely as fire-proxies or as evidence for deliberately heat-treated lithics (for exceptions, see Copeland 1998, Duttine et al. 2005).

IV.V: Burnt Bone.

Bones are the last set of objects which can be burnt in fires, and survive to act as a proxy. This happens in four main ways; burned in sediment beneath hearths, burned through cooking meat on them, burned in hearths as waste; and burned in hearths as fuel. The first category may of course include unburned bones that were buried, and then burnt in the sediment down to c.15cm. Calcination (whiteness) only occurs in bones in the flames, whereas buried bone may be carbonized (de Becdelievre et al. 2015, Stiner et al. 1995, p.231). Combustion of fleshed bone (cooking) differs from that of defleshed bone. Below 300°C, overlying fat slows down burning, whilst over 800°C it increases it (Bohnert et al. 1998). Fat and flesh provide additional fuel around the bone, potentially heating it to higher temperatures; however, in intentional cooking, meat should not be burned, as that reduces its calorific value. Instead, meat often shields the bone, and encased bone reaches only half the temperature of surface meat (Koon 2006, Koon et al. 2003). Neanderthals had population-level "cooking genes" (see p.122 and Carmody et al. 2016 for details); with meat-heavy diets, cooked bones may originally have been common. Cooked bone can be determined through differential burning, whereby bone ephiphyses, less meat-covered, burn more than diaphyses. In addition, bone cyanamide forms due to heating alongside ammonia (Habelitz et al. 2001). This ammonia comes from nearby graphitic fuels (coal), or organic-rich fuels (dung), or more likely from organic material on the bone itself, suggesting that meat was heated on the bone (Snoeck et al. 2014).

Burnt bones are most obviously coloured; black (carbonized) at c.200-400°C or white (calcined) at 600°C+ (Bennett 1999). However, depending on proximity to the fire, or any sediment buffering, these changes can be patchy (Perez et al. 2017). As with forming charcoal or ash, oxygen availability also influences colouration; oxidisation causes white calcination, but reduction cause blue-grey colours (Squires et al. 2011). This could determine which bones were heated in sub-hearth sediments (reducing environments), and which were on the fire itself – however, reducing environments also occur within active fires (Albini 1993). Confusing bone colourations can be caused by surrounding environments, even without fire. Copper or iron leaching creates greens and reds; haemoglobin and manganese dioxide causes browns and blacks respectively, which can be more easily confused with burning (Nicholson 1993, Shipman et al. 1984). Colouration should be combined with other fire signatures to infer fire use. However, this introduces a paradox in that if other fire evidence is present, bones are denoted "burnt" and fire proxies are strengthened, whereas if other fire is rare, this potential evidence is dismissed. However in most instances colour is not the primary property of burnt bone.

Burnt bone, as with burnt lithics, may be transferred from fire-using sites to fireless ones, creating false fire signatures at the second site. However this does not negate fire evidence at the first site, as other proxies may survive. If meat was not traded between Neanderthal groups, then it still evidences one *group's* fire, if not a *site's* fire. Inter-site transfer is less probable if use/absence of fire were seasonally determined. Unlike lithics, which are used for many years, cooked meat only lasts days or weeks; thus probably only surviving one site transfer. If a Neanderthal used fire in all winter sites, but at no summer ones, then only one such transfer out of perhaps two each year (assuming seasonal camp movement – Sanchez-Hernandez et al. 2014) would be from fire-using to fireless sites to cause such interpretative problems. Furthermore, although bones are light, they introduce unnecessary weight for travel. Although eating off bones would have been common within camps, for inter-site transfer of resources, Neanderthals most likely filleted and packaged meat to save both space and weight, leaving bones behind at the site where they were burnt. The caveat to this is worked bone tools (although not used by many Neanderthals until the Chatelperronian – d'Errico et al. 2003), which could be carried for many years. However, a) the burnt bone studied refers to unworked burnt bone, and b) Neanderthals would not have deliberately burnt bones for toolmaking, or chosen pre-burnt bone to make tool out of, as burning does not improve its properties, rather weakening and fracturing it.

As well as colour change, heating also changes a bone's Crystallinity Index (CI). Larger, uniform apatite crystals are formed following Ostwald ripening processes, whereby inter-crystal bonds are destroyed and the space reduced between them (McKinley 2000). Structural carbonate and CO_3 radicals are lost in carbonate hydroxlapatite while phosphate is introduced and homogeneous B-tricalciumphosphate is formed (Ibid, Munro et al. 2007, Person et al. 1996). Bone collagen melts at 215°C, facilitating this process. However, collagen can be damaged by burial environments as well as by fire (Koon 2006). This increased crystal size can be measured by X-ray diffraction (Piga et al. 2009) or Fourier Transform Infrared Spectroscopy (FTIR - Lozano et al. 2002), and can be detected by narrower and sharper peak profiles (Pijoan et al. 2007). Crucially for Palaeolithic sites however, bone crystallinity naturally increases over time, so both unburnt and burnt bone have similar crystallinity values after 10,000 years (Stiner et al. 1995). This proxy is therefore unsuitable for measuring burning on Middle Palaeolithic bone. The only use for it might be where uniform X-ray diffraction or FTIR is carried out on many bones in sites of similar age and burial condition – any differences in crystallinity may indicate burning on some and not on others. Comparison with modern reference sets however would be useless.

Increased crystallinity often causes bone fragmentation during heating. Cracking occurs due to steam pressure unable to escape – in broken bones it escapes through the ends, but splits whole ones (Costamagno et al. 2005). However, unlike fragmentation of heated lithics, which is distinct from human knapping practices, bone fragmentation from heating resembles bones smashed to access marrow, or post-burial taphonomic fragmentation (Johnston 1989, Karr 2012). It is easy to tell whether bones were fractured when fresh or dry (Green and Schultz 2017, Oliver 1993), but this indicates little about modes of fragmentation; fresh bone can be burnt either from cooking or as fuel, and dry bone can be burnt either as waste disposal or in sediment beneath fires. Whether broken by fire action or not, 98% of all bone fragments on prehistoric sites are <2cm (Yravedra et al. 2016), and deciphering how they were broken from this jigsaw is tricky. However, in bones broken by humans or natural percussion movement, cracks originate from arbitrary points of force where the bone was struck, running along the long axis of the bone; and compression fractures form along the same axis as the direction of force. In fire, fractures originate from innate weaknesses in bone structures such as surface pores (McKinnon et al. 2021, Ortner and Putschar 1981). However, at least partially-complete bones are required to reconstruct fracture patterns, which is often impossible. Fire-cracking causes rapid propagation characteristics similar to hammering, and different from trampling/crushing, due to heated bones' reduced energy-absorbing capabilities (Herrmann and Bennett 1999). However, Neanderthals certainly extracted bone marrow by hammering, possibly heating bone to facilitate this. It is impossible to differentiate modes of fragmentation from crack propagation speeds; this would only be useful when detecting non-anthropogenic fire (e.g. volcanic eruptions). Low-level burning causes cracking and peeling of cortical surfaces (Chang 2023, Nicholson 1993), although taphonomic processes also cause this.

I have briefly mentioned breaking and irreversible denaturation of collagen molecules through heating; this can be examined *in absentia* of changes to crystallinity. Differential Scanning Calorimetry (DSC) can distinguish denatured from ordinary collagen in only 30 minutes, as degraded molecules have wider DSC peaks (Koon 2006). Transmission Electron Microscopy (TEM) can visually study molecules, differentiating unaltered (with equal diameters), partially denatured (beaded, localised melted areas, bulbous melted "dumbbells" on both fibril ends) and fully denatured (amorphous samples without banding) (Koon et al. 2010, Richter 1986). Other chemical changes from heating include converting glycine to glutamic acid (Taylor et al. 1995, Weiss et al. 2018), carbon: nitrogen ratios (increased C and decreased N content at 200-450°C – Reidsma et al. 2016) and oxygen isotope ratios (δ18Op values decrease by up to 7‰ above 300°C due to oxygen exchange between bone bioapatite and water vapour by atmospheric exposure of the former – Munro et al. 2007). However, diagenesis influences all of these over time. Similar to issues with crystallinity, these methods should not use modern reference samples, but can instead detect intra-sample differences, to determine if spatial clusters of non-visually altered bone could represent hearths.

A final consideration is variable burning within an assemblage due to the nature of the bones themselves. Different animal bones burn differently; those of smaller animals fracture less, either from heat or taphonomy (Steffen and Mackie 2005), and the same issue applies to different bones within single carcasses. Fish bones are consistently darker than mammal/bird bones at the same temperature (Nicholson 1995). Within a species, older individuals have more cross-links in bones, preventing heat-related swelling and fracturing along fibrils (Koon 2006). Many bone heating studies focus on human bone from archaeological cremation or modern forensic studies. This differs from animal and Neanderthal bone, as robust Neanderthal bones may have withstood heating better than modern human ones. Archaeological reports of burnt bone in Neanderthal contexts are common, as fire proxies and evidence of cooking. However, in all papers I researched, the authors used visual criteria to determine their state. Whilst some of these may have been erroneous, attributing natural causes to anthropogenic burning, I believe that if more archaeological bones were more closely studied using a combination of other criteria, this would expand the number of Middle Palaeolithic sites containing burnt bone, as well as more conclusively demonstrating the nature of the evidence already seen.

V: Conclusion.

From this chapter, we can see that Neanderthals most certainly used fire, and the question for this species is not the presence/absence question for earlier hominin fire use, but rather a comparison with our own species, in terms of frequency of fire use, its complexity, and whether these fires were started *at will*. I have examined five proxies; charcoal, ash, burnt sediment, burnt lithics and burnt bone. The overall picture is that these proxies often miss fire use; many fired objects cannot be visually inspected for fire, and transformations can be only picked up through further modern scientific techniques. Secondly, these proxies also tend to decline through time, sometimes through physical destruction of the objects, sometimes with the aspect that fire changed (e.g. burnt bone crystallinity) declining through time and tending towards values of unburnt objects.

As a result, whereas a proxy definitely shows proof of fire at a particular location (excepting rare cases of misidentifying magnesium oxide staining), the absence of a particular proxy does not prove the lack of fire in the first place. Sometimes, of course, that proxy never existed even though the fire did; lithics and bones are not always introduced to anthropogenic fires, so naturally-burnt lithics and burnt bone are not to be expected in all fire-using sites. But it demonstrates that proxies should generally be used in combination. Whilst by no means foolproof (due to different taphonomic conditions between sites), more different proxies at a site, indicates that more fire was originally present. A single fire leaves few traces (barring exceptional preservation circumstances), whereas many will leave notable palimpsests; bones and lithics are more likely to be burned by multiple fires, charcoal and ash layers will be thicker, and rubified sediments will be darker, and both more noticeable after repeated re-burnings. Using these proxies, the next chapter addresses the presence or absence of fire in over 230 Neanderthal sites across Europe and the Near East.

Chapter Three: Neanderthal Fire Frequency.

Neanderthals were among the earliest fire users, although fire may not have become an evolutionarily-obligate technology until the Upper Palaeolithic or later. I have discussed fire proxies, their various prevalences and taphonomic resistances. Charcoal is resilient and frequently recognised, whilst ash and burnt sediment form more ephemeral layers. The presence of discrete hearth features strongly depends on taphonomic preservation, and whether the hearth was exposed, or sheltered in pits or hollows. Finally, whereas burnt bone and lithics occur frequently, non-visual evidences of burning here require seldom-available and invasive scientific procedures. Based on these proxies, this chapter addresses a key primary thesis question, *What evidence is there that H. neanderthalensis used fire commonly as a species*? I provide an original comparison of published data from 237 Neanderthal and Transitional sites, concluding that controlled fire, in some form, is present in most Neanderthal sites. The conclusions (e.g. Dibble et al. 2018) that Neanderthals did not generally use fire are not supported. Apparent differences between Neanderthal cave and open-air sites are discussed, and could either be attributable to differential taphonomic processes between the two site types, or differential fire use, with fire being much more common in caves. From this, I conclude that pyrotechnic technology was sufficiently important across many Neanderthal sites for it to be likely to elucidate novel Neanderthal lifeways that we previously have not studied, and, furthermore, that caves are the sites we are most likely to find it in.

I use five sub-proxies of hearths to indicate fire's existence; charcoal, ash, burnt, sediment, burnt bone and burnt lithics. Hearth survival varies too strongly to be a reliable indicator; hearths instead evidence definite *intentionality*. Whilst discrete hearths are undeniably of anthropogenic origin, scattered remains could be from natural wildfire or volcanic events. Each proxy is only considered on a presence-absence basis on each site, throughout all layers. This is for two reasons: firstly, quantifying relative prevalences of fire per layer is often impossible, even in well-documented sites, due to unknown archaeological losses. Different sites cannot be compared for relative prevalence due to different eras and excavation techniques. Within a single site, each layer has different taphonomic histories, with non-comparable survival conditions. Secondly, many brief/older publications do not tie combustion features to particular strata, although noting their association with particular technocomplexes, preventing proper layer-by-layer comparisons. My methodology's disadvantage is that it does not take quantity into account (see Sandgathe 2017 for further critiques of this approach).

Abric Romani, with multiple overlapping hearths, and Jarama VI with only one hearth, will score identically. However, other fire proxies, which become ever more noticeable with more hearths present, may give sites such as Abric Romani higher scores. This is also key to my analysis, as I assume that higher numbers of proxies, and thus higher scores, represents more frequent fire use in that site. Scores are calculated by adding the number of proxies together. More original fire might leave more evidence today, and higher chances of perfect scores (5/5). This however depends on taphonomy and investigative scales for each site; well-studied sites with few hearths might provide all proxies, and badly-preserved sites with many original fires may have lost all charcoal and ash. However, given the impossibility of correcting for differential taphonomic effects, it is nevertheless valuable to collate statistical information on fire proxies from the archaeological record.

I: Methodology.

Through a literature evaluation of published sites (conducted in 2021), I evaluate 237 Mousterian Neanderthal sites; 169 caves, and 59 open-air sites. 'Mousterian' refers to sites containing Mousterian, or Mode 3, lithic tools manufactured by *H. neanderthalensis*. I additionally include 9 Transitional cave sites (Late Neanderthal sites containing non-Mousterian technocomplexes), to see if any differences occur between Mousterian and Transitional Neanderthal groups, and if contemporary *H. sapiens* influenced the latter at all. Each site is scored out of five (each fire proxy except hearths, which as aforementioned is not a distinct proxy, but composed of several others in 'hearth' units). This dataset is unique; regrettably, a comparable one does not currently exist for modern humans, especially in the Upper Palaeolithic. Murphree and Aldeais (2022) and Scott and Hosfield (2021), for the Upper and Lower Palaeolithic respectively, provide the closest comparisons, which only focus on fire-using sites and exclude fireless ones. Murphree and Aldeais in particular note that out of 164 fire-using sites, 68% (111) had little detailed information on fire. This would make further categorisations of their works into my five fire proxy criteria difficult although valuable, but this is beyond the scope of this thesis.

I utilised internet and library resources for papers and books on relevant sites (references in Tables 3.2, 3.4 and 3.6 below); I omit sites with insufficient information on them to form valid conclusions as to the presence/absence of fire. For a site to be considered, at least one paper must have been written either detailing excavation procedures or specifically examining fire use there. A natural bias may result from more papers being associated with more famous sites. References are for papers which include information on fire proxies; for fireless sites, I either cite papers researching fire use and finding none, or those discussing the site in greatest depth. I omitted several sites with unspecified "hearths": Barma Grande, Fuentes de San Cristobal and Gura Cheii-Rasnov (caves), and Il'skaya and San Quirce (open-air). Several papers with additional scientific procedures (e.g. FTIR or micromorphology) are included in Table 3.1 beneath. Differences noted here may be due to technology, particularly micromorphology and magnetism, picking up fire residues invisible to the naked eye. However, they may also result from such sites already having intense occupation and interesting archaeology, and thus being thought worthy of further research techniques. The cause-and-effect link between new investigative techniques and discovering fire proxies is unclear.

Table 3.1: The different scientific techniques looking for fire on various Middle Palaeolithic sites. The score in the third column represents how many different fire proxies (charcoal, ash, burnt sediment, burnt bones, burnt lithics) are found in that site. Higher scores probably mean more original fire use.

Scientific Technique	**Sites**	**Scores out of 5**	**Average Score**
Micromorphology	Abrigo del Molino, Arbreda Cave, Cova del Gegant, Crvena Stijena, Ein Qashish, El Esquilleu, Grotte XVI, Grotte du Lazaret, Jarama IV, Nesher Ramla, Oscurusciuto Rockshelter, Roc de Marsal, Vanguard Cave	1, 2, 4, 5, 1, 4, 5, 3, 3, 5, 5, 5, 4	3.62
Magnetism	Amud Cave, Crvena Stijena, Grotte du Lazaret, La Ferrassie	4, 5, 3, 3	3.75
FTIR (Fourier Transform Infrared Spectroscopy)	Cova del Gegant, El Esquilleu, Theopetra, Boker Tachtit Rockshelter (Transitional)	4, 4, 3, 2	3.25
Thin Sections	Tabun, Theopetra	5, 3	4
GIS	Quneitra	1	1

II: Results.

Table 3.2: Middle Palaeolithic cave sites and corresponding fire proxies. The second column, hearths, does not represent one of the studied proxies as it is the most taphonomy-dependent, but is noted as it is the only attribute that means the fires were of undeniably anthropogenic origin. The following five columns represent the five proxies used to calculate the final score.

Neanderthal Cave Sites

Site	Hearths	Burnt Sediment	Charcoal	Ash	Burnt Lithics	Burnt Bone	Score out of 5	References (year of first excavation/publication)
Abri de Merveilles	✗	✗	✗	✗	✗	✗	0	Sisk 2011 **(excv. 1926)**
Abri du Maras	✗	✓	✓	✓	✓	✓	5	Daujeard et al. 2017 **(Gilles 1950)**
Abric del Pastor	✓	✓	✓	✓	✓	✓	5	Machado et al. 2019, Vidal-Matutano et al. 2017 **(excv. 1953)**
Abric Romani	✓	✓	✓	✓	✓	✓	5	Courty et al. 2012, Vaquero et al. 2001, Vallverdu et al. 2012 **(Vidal 1911)**
Abrigo de Humo	✗	✗	✓	✗	✗	✗	1	Ramos Fernandez et al. 2012 **(excv. 1965)**
Abrigo de la Quebrada	✓	✓	✓	✓	✗	✗	3	Carrion Marco et al. 2019 **(excv. 2004)**
Abrigo del Molino	✗	✗	✓	✗	✗	✗	1	Kehl et al. 2018 **(excv. 2013, Alvarez-Alonso et al. 2014)**
Aguilon P5	✓	✓	✓	✓	✗	✓	4	Mazo and Alcolea 2020 **(Cuenca-Bescos et al. 2010)**
Aguilon P7	✗	✗	✗	✗	✗	✗	0	Mazo and Alcolea 2020 **(Cuenca-Bescos et al. 2010)**
Ain Difla	✗	✗	✓	✓	✓	✗	3	Lindly and Clark 1987 **(excv. 1984, Clark et al. 1987)**
Amalda	✓	✗	✗	✗	✗	✓	1	Sanchez-Romero et al. 2020 **(excv. 1979, Altuna 1990)**
Amud	✓	✓	✗	✓	✓	✓	4	Alperson-Afil and Hovers 2005, Madella et al. 2002, Rabinovich and Hovers 2004 **(excv. 1961, Suzuki and Takai 1970)**
Amutxate	✗	✗	✗	✗	✗	✗	0	Torres et al. 2007 **(excv. 1988)**
Arbreda	✗	✗	✓	✗	✗	✓	2	Kehl et al. 2014, Lloveras 2010 **(excv. 1972, Soler and Maroto 1987)**

Site	Hearths	Burnt Sediment	Charcoal	Ash	Burnt Lithics	Burnt Bone	Score out of 5	References
Arlanpe	✗	✗	✗	✗	✗	✗	0	Rios-Garaizar et al. 2015 **(excv. 2006, Rios-Garaizar et al. 2013)**
Arma Veirana	✗	✓	✓	✗	✗	✓	3	Charolla 2015, Hirniak et al. 2020 **(excv. 2015)**
Bajondillo	✗	✗	✓	✓	✗	✗	2	Cortes-Sanchez et al. 2019 **(excv. 1989, Cortes Sanchez and Vallejo 1997)**
Bau de l'Aubesier	✗	✗	✓	✓	✓	✓	4	Lebel et al. 2001 **(Moulin 1904)**
Baume Moula Guercy	✓	✗	✗	✗	✗	✓	1	Valensi et al. 2012 **(excv. 1975)**
Baume-Vallee	✗	✗	✓	✗	✓	✓	3	Gala et al. 2005, Raynal et al. 2012 **(excv. 1963, Bayle des Hermens and Laborde 1965)**
Bezez	✓	✓	✗	✗	✗	✗	1	Copeland 1978 **(excv. 1963)**
Bisitun	✗	✗	✗	✗	✗	✗	0	Oakley 1962 **(excv. 1949, Coon 1951)**
Bisnik	✓	✗	✓	✗	✓	✓	3	Cyrek et al. 2010 **(excv. 1991, Pelisiak 1993)**
Bison Cave	✓	✓	✗	✓	✓	✓	4	Courty 2017 **(excv. 1958)**
Bojnice I	✗	✓	✓	✗	✗	✓	3	Neruda and Kaminska 2013 **(Prosek 1952)**
Bolomor	✓	✗	✓	✓	✓	✓	4	Sanudo et al. 2016 **(excv. 1989, Fumanal 1993)**
Boquete de Zafarraya	✓	✗	✓	✗	✗	✓	2	Caparros et al. 2012 **(excv. 1981, Barroso Ruiz et al. 1983)**
Bordes-Fitte	✗	✗	✗	✗	✓	✗	1	Aubry et al. 2012 **(excv. 1949, Bordes and Fitte 1950)**
Bruniquel	✓	✓	✗	✗	✗	✓	2	Jaubert et al. 2016 **(Rouzaud et al. 1996)**
Buran Kaya III	✗	✗	✗	✗	✗	✓	1	Laroulandie and d'Errico 2004, Pean et al. 2013 **(excv. 1990)**
Carihuela	✗	✗	✓	✗	✗	✗	1	Carrion et al. 2019 **(excv. 1954, Spahni 1955)**
Chez-Pinaud Jonzac	✗	✗	✗	✗	✓	✓	2	Niven et al. 2012 **(excv. 1998)**
Ciemna	✓	✓	✓	✗	✗	✓	3	Valde-Nowak et al. 2014 **(excv. 1912, Czarnowski 1924)**

Site	Hearths	Burnt Sediment	Charcoal	Ash	Burnt Lithics	Burnt Bone	Score out of 5	References
Combe-Grenal	✓	✓	✓	✗	✓	✗	3	Bowman and Sieveking 1983, Garralda et al. 2005 **(excv. 1953, Bordes and Prat 1965)**
Cova del Gegant	✓	✓	✓	✓	✗	✓	4	Daura et al. 2010, Sanz et al. 2015 **(excv. 1952, Vinas 1972)**
Cova del Rinoceront	✗	✗	✓	✗	✓	✗	2	Daura et al. 2015 **(excv. 2002, Daura et al. 2005)**
Cova Eiros	✗	✗	✗	✗	✗	✗	0	Rey-Rodriguez et al. 2016 **(Grandal-D'Anglade 1993)**
Cova Foradada	✗	✗	✓	✗	✗	✓	2	Morales et al. 2019, Rodriguez Hidalgo et al. 2018 **(excv. 1997)**
Cova Gran	✓	✓	✓	✓	✓	✓	5	Benito-Calvo et al. 2009 **(excv. 2004)**
Cova Negra	✓	✗	✗	✗	✓	✓	2	Arsuaga et al. 2009, Martinez Valle et al. 2016, Richards et al. 2019 **(Vines 1928)**
Covalejos	✗	✗	✗	✗	✗	✓	1	Yravedra-Sainz de los Terreros et al. 2015 **(excv. 1872, de Sautuola 1880)**
Coygan	✗	✗	✓	✗	✗	✗	1	Aldhouse-Green et al. 1995 **(excv. 1866, Hicks 1867)**
Crvena Stijena	✓	✓	✓	✓	✓	✓	5	Bakovic et al. 2009 **(excv. 1956, Brodar 1958)**
Cueva Anton	✓	✗	✓	✗	✗	✓	2	Angelucci et al. 2013 **(excv. 1991, Martinez 1997)**
Cueva del Camino	✗	✗	✓	✗	✗	✗	1	Arsuaga et al. 2012 **(excv. 1980, Alferez et al. 1982)**
Cueva del Conde	✗	✗	✗	✗	✗	✗	0	Lopez-Garcia et al. 2011a **(excv. 1915)**
Cueva Morin	✗	✗	✓	✗	✗	✗	1	Maillo-Fernandez et al. 2014 **(excv. 1917, Carballo 1923)**
Cunji	✓	✗	✓	✓	✓	✗	3	Baumler and Speth 1993 **(Field 1951)**
Dederiyeh	✓	✓	✓	✓	✓	✓	5	Akazawa and Nishiaki 2017, Akawawa et al. 1995, 1999 **(excv. 1989)**
De Nadale	✓	✗	✓	✗	✗	✓	2	Livraghi et al. 2019 **(excv. 2006)**

Site	**Hearths**	**Burnt Sediment**	**Charcoal**	**Ash**	**Burnt Lithics**	**Burnt Bone**	**Score out of 5**	**References**
Devil's Tower	✓	✓	✓	✗	✗	✓	3	Garrod et al. 1928 **(excv. 1926)**
Divje Babe I	✓	✓	✓	✗	✗	✓	3	Turk and Kosir 2017 **(excv. 1980)**
Djruchula	✗	✗	✓	✓	✗	✗	2	Mercier et al. 2010 **(excv. 1958)**
Do-Ashkaft	✗	✗	✓	✗	✗	✗	1	Biglari and Heydari 2015 **(excv. 1996, Biglari and Heydari 2001)**
Douara	✓	✓	✓	✓	✓	✓	5	Griggo 2004, Niskiaki and Akazawa 2015 **(excv. 1970, Akazawa et al. 1973)**
El Castillo	✓	✗	✓	✓	✗	✗	2	Pike-Tay et al. 1999, Rink et al. 1997 **(excv. 1903, Alcade del Rio et al. 1912)**
El Esquilleu	✓	✓	✓	✓	✗	✓	4	Cabanes et al. 2010, Cuartero et al. 2015, Mallol et al. 2010 **(excv. 1997, Baena et al. 1999)**
El Miron	✗	✗	✓	✓	✗	✓	3	Marin-Arroyo et al. 2018 **(excv. 1996)**
El Salt	✓	✓	✓	✓	✓	✓	5	Machado and Perez 2016, Vidal-Matutano et al. 2017 **(excv. 1986, Galvan et al. 2001)**
Emanuel	✓	✗	✗	✗	✓	✗	1	Goder-Goldberg et al. 2012, Peleg et al. 2010 **(excv. 2006)**
Es'Skhul	✗	✓	✗	✗	✓	✗	2	Mercier et al. 1993, Salomon et al. 2012 **(excv. 1931, McCown and Keith 1939)**
Fossellone	✓	✓	✓	✗	✓	✗	3	Degano et al. 2019, Vitagliano and Bruno 2012 **(excv. 1936, Blanc 1937)**
Galeria de las Estatuas	✗	✗	✓	✗	✗	✓	2	Arsuaga et al. 2017 **(excv. 2008)**
Gatzarria	✗	✗	✗	✗	✗	✓	1	Deschamps 2019, Ready 2013 **(excv. 1950)**
Geissenklosterle	✗	✗	✓	✗	✓	✓	3	Conard et al. 2019 **(excv. 1973, Hahn 1988)**
Ghamari	✗	✗	✗	✗	✗	✗	0	Bazgir et al. 2014 **(Hole and Flannery 1967)**

Site	**Hearths**	**Burnt Sediment**	**Charcoal**	**Ash**	**Burnt Lithics**	**Burnt Bone**	**Score out of 5**	**References**
Ghari-i-Mordeh Gusfand	✗	✗	✗	✗	✗	✗	0	Dupree et al. 1970 **(excv. 1969)**
Ghiardo	✓	✗	✓	✗	✓	✗	2	Cremaschi et al. 2015 **(Cremaschi and Christopher 1984)**
Gilvaran	✗	✗	✗	✗	✗	✗	0	Bazgir et al. 2014 **(excv. 2014)**
Gorham's Cave	✓	✓	✓	✓	✓	✓	5	Barton and Jennings 2012, Finlayson et al. 2008a, MacPhail and Goldberg 2000, Stringer et al. 1999 **(Waechter 1951)**
Grotta Breuil	✗	✗	✓	✗	✓	✓	3	Grimaldi and Spinapolice 2010 **(excv. 1936, Blanc 1938)**
Grotta dei Moscerini	✓	✗	✓	✓	✗	✓	3	Villa et al. 2020 **(excv. 1949)**
Grotta dei Santi	✓	✓	✓	✓	✗	✓	4	Spagnolo et al. 2020b **(Salvagnoli and Marchetti 1843)**
Grotta della Ghiacciaia	✓	✓	✓	✓	✗	✗	3	Ferraris et al. 1990 **(excv. 1979)**
Grotta di Fumane	✓	✓	✓	✓	✓	✓	5	Romandini et al. 2014, Tagliacozzo et al. 2013 **(excv. 1988)**
Grotta Grande	✓	✗	✓	✓	✗	✓	3	Ronchitelli et al. 2011 **(Fusco 1961)**
Grotta Guattari	✗	✗	✗	✗	✗	✓	1	Stiner 1991 **(excv. 1939, Blanc 1942)**
Grotta Paglicci	✗	✗	✗	✗	✓	✗	1	Crezzini et al. 2016 **(excv. 1961)**
Grotta Reali	✓	✓	✓	✓	✓	✓	5	Cui et al. 2009 **(excv. 2001)**
Grotte XVI	✓	✓	✓	✓	✓	✓	5	Karkanas et al. 2002 **(excv. 1983, Rigaud et al. 1995)**
Grotte de la Verpilliere	✗	✗	✓	✗	✗	✓	2	Frick 2016 **(excv. 1868, Meray 1869)**
Grotte des Barasses II	✗	✓	✓	✗	✓	✓	4	Rufa et al. 2018 **(excv. 1967)**
Grotte du Lazaret	✓	✓	✗	✓	✗	✓	3	Valensi et al. 2013 **(Octobon 1965)**
Grotte du Renne	✓	✓	✗	✗	✗	✗	1	Salomon et al. 2012 **(excv. 1949, Leroi-Gourhan 1964)**
Grotte Mandrin	✓	✗	✓	✓	✓	✓	4	Vandevelde et al. 2017 **(excv. 1990)**
Gruta da Oliveira	✓	✓	✓	✓	✗	✓	4	Angelucci and Zilhao 2009 **(excv. 1989)**

Site	**Hearths**	**Burnt Sediment**	**Charcoal**	**Ash**	**Burnt Lithics**	**Burnt Bone**	**Score out of 5**	**References**
Gruta do Caleirao	✗	✗	✗	✗	✗	✓	1	Lloveras et al. 2011 **(excv. 1979, Zilhao 1992)**
Gruta Nova da Columbeira	✓	✓	✓	✓	✗	✓	4	Zilhao et al. 2011 **(excv. 1962, Ferembach 1964)**
Hayonim	✓	✓	✓	✓	✓	✓	5	Bar-Yosef et al. 2017, Mercier et al. 2007, Weiner et al. 2002 **(excv. 1965, Bar-Yosef and Tchernov 1967)**
Higueral de Valleja	✗	✗	✓	✓	✗	✓	3	Jennings et al. 2009 **(excv. 1979)**
Hovk I	✗	✗	✓	✓	✗	✗	2	Bar-Oz et al. 2012, Pinhasi et al. 2011 **(excv. 2005, Pinhasi et al. 2008)**
Jarama VI	✓	✓	✓	✗	✓	✗	3	Kehl et al. 2013 **(Pardo 2001)**
Kabazi V	✓	✗	✗	✓	✗	✓	2	Burke 2000, Uthmeier and Chabai 2018 **(Formozov 1959)**
Kalamakia	✓	✗	✓	✗	✗	✓	2	Darlas and de Lumley 1999 **(excv. 1993, de Lumley et al. 1994)**
Kaldar	✗	✗	✓	✗	✓	✓	3	Bazgir et al. 2017 **(excv. 2011, Bazgir et al. 2014)**
Karabi Tamchin	✓	✗	✗	✗	✗	✓	1	Anderson and Burke 2009, Yevtuskenko et al. 2003 **(excv. 1999)**
Kebara	✓	✓	✓	✓	✓	✓	5	Albert et al. 2012, Meignen et al. 2017, Speth and Tchernov 2001 **(excv. 1927, Garrod 1955)**
Kobeh	✗	✗	✗	✗	✗	✗	0	Marean and Kim 1998 **(excv. 1959)**
Krapina	✓	✗	✓	✗	✓	✓	3	Radovcic et al. 2015, 2020, Simek and Smith 1997, Trinkaus 1985 **(Gorjanovic-Kramberger 1899)**
Ksar Akil	✗	✓	✗	✓	✗	✓	3	Ewing 1947, Douka et al. 2013, Kersten 1991 **(excv. 1937)**
Kulna	✓	✓	✓	✗	✗	✗	2	Neruda 2017 **(excv. 1880, Breuil 1924)**
La Combette	✓	✓	✓	✓	✓	✓	5	Audiard et al. 2019, Texier et al. 2003 **(excv. 1987)**

Site	Hearths	Burnt Sediment	Charcoal	Ash	Burnt Lithics	Burnt Bone	Score out of 5	References
La Crouzade	✓	✓	✓	✗	✗	✓	3	Saos et al. 2020 **(Rousseau 1874)**
La Ferrassie	✓	✓	✓	✗	✗	✓	3	Bertran et al. 2008 **(Peyrony 1934)**
La Guelga	✓	✓	✗	✓	✗	✓	3	Menendez et al. 2017, Sanchis et al. 2019 **(excv. 1989, Menendez and Martinez Villa 1992)**
Lakonis	✓	✓	✓	✓	✓	✓	5	Harvati et al. 2003, Panagopoulou et al. 2014 **(excv. 1999)**
La Roca dels Bous	✓	✓	✗	✓	✗	✗	2	Benito-Calvo et al. 2009, Martinez-Moreno et al. 2004 **(excv. 1988)**
Las Callejuelas	✗	✗	✗	✗	✗	✗	0	Domingo et al. 2017 **(excv. 1975, Eisemann et al. 1993)**
La Vina	✗	✗	✓	✗	✗	✗	1	De la Rasilla et al. 2020 **(excv. 1980, Fortea 1981)**
Le Moustier	✓	✗	✗	✓	✓	✓	3	Gravina and Discamps 2015 **(de Mortillet 1872)**
Les Auzieres II	✗	✗	✗	✗	✗	✗	0	Marchal et al. 2009 **(excv. 2001)**
Les Canelettes Aveyron	✓	✗	✓	✗	✗	✓	2	Cochard et al. 2012 **(excv. 1964)**
Les Pecheurs	✓	✗	✓	✗	✓	✓	3	Moncel et al. 2008 **(Lhomme 1983)**
Lezetxiki II	✗	✗	✗	✗	✗	✗	0	Arriolabengoa et al. 2015 **(excv. 1956)**
Llonin	✗	✗	✓	✗	✗	✗	1	De la Rasilla et al. 2020 **(excv. 1971)**
Los Casares	✗	✗	✓	✗	✗	✗	1	Alcaraz-Castano et al. 2017, Mazo and Alcolea 2020 **(excv. 1966, Barandiaran 1973)**
Mezmaiskaya	✗	✗	✗	✗	✗	✓	1	Skinner et al. 2005 **(excv. 1987, Golovanova 1995)**
Misliya	✓	✓	✓	✓	✗	✓	4	Weinstein-Evron et al. 2017, Yeshurun et al. 2007 **(Olami 1984)**
Molare	✓	✓	✓	✓	✗	✗	3	Spagnolo et al. 2020a **(excv. 1984, Mallegni and Ronchitelli 1987)**
Mujina Pecina	✓	✗	✓	✗	✗	✓	2	Miracle 2005 **(Malez 1979)**

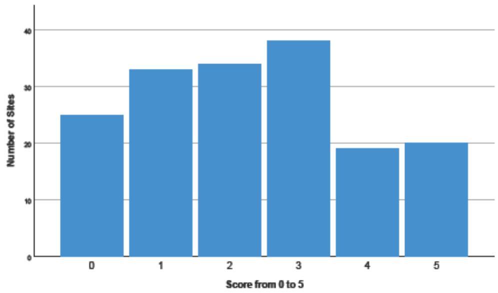
Site	Hearths	Burnt Sediment	Charcoal	Ash	Burnt Lithics	Burnt Bone	Score out of 5	References
Navalmaillo	✓	✗	✓	✗	✓	✓	3	Abrunhosa et al. 2014, Arriaza et al. 2017, Marquez et al. 2013, Sanchez-Romero et al. 2017 **(excv. 2002)**
Noisetier	✓	✗	✓	✗	✗	✓	2	Costamagno 2013 **(Allard 1993)**
Orvale Klde	✗	✗	✗	✗	✓	✓	2	Bar-Oz and Adler 2005 **(excv. 1973, Tushabramishvili et al. 1999)**
Oscurusciuto	✓	✓	✓	✓	✓	✓	5	Spagnolo et al. 2019 **(excv. 1998)**
Payre	✗	✗	✗	✓	✓	✓	3	Moncel and Rivals 2011, Valladas et al. 2008 **(Combier 1967)**
Pech de l'Aze IV	✓	✓	✓	✓	✓	✓	5	Niven 2013, Sandgathe et al. 2011 **(excv. 1970, Bordes 1975)**
Portel Ouest	✗	✗	✗	✗	✗	✗	0	Gardeisen 1999 **(excv. 1920)**
Prado Vargas	✗	✓	✓	✗	✗	✓	3	Navazo Ruiz et al. 2021 **(excv. 1986)**
Prolom II	✓	✗	✗	✗	✓	✗	1	Enloe et al. 2000, Stepanchuk 1993 **(excv. 1977, Kolosov 1986)**
Qafzeh	✓	✓	✗	✓	✓	✓	4	Hovers 2004, Hovers et al. 1997, 2003, Rabinovich et al. 2004 **(excv. 1933, Neuville 1951)**
Qaleh Bozi II	✗	✗	✓	✓	✗	✗	2	Biglari et al. 2009 **(excv. 2005)**
Qaleh Bozi III	✗	✗	✗	✗	✗	✗	0	Biglari et al. 2009 **(excv. 2005)**
Qaleh Kurd	✗	✗	✗	✗	✗	✗	0	Soleymani and Alibaigi 2018 **(Soleymani and Alibaigi 2012)**
Raj Cave	✗	✗	✓	✗	✓	✗	2	Patou-Mathis 2004 **(excv. 1963)**
Ramandils	✗	✗	✗	✗	✓	✓	2	Rusch et al. 2019 **(excv. 1983, Boutie et al. 1998)**
Ras el-Kelb	✓	✗	✗	✗	✓	✓	2	Garrard 1998 **(excv. 1958, Garrod and Kurkbride 1961)**
Rio Secco	✓	✓	✓	✗	✓	✓	4	Peresani et al. 2014 **(excv. 2002, Peresani and Gurioli 2007)**

Site	Hearths	Burnt Sediment	Charcoal	Ash	Burnt Lithics	Burnt Bone	Score out of 5	References
Riparo Bombrini	✓	✓	✓	✗	✗	✗	2	Riel-Salvatore et al. 2013 **(excv. 1976, Vicino 1984)**
Riparo Tagliente	✗	✗	✗	✗	✗	✗	0	Thun Hohenstein et al. 2018 **(excv. 1962)**
Roc de Marsal	✓	✓	✓	✓	✓	✓	5	Aldeais et al. 2012 **(excv. 1953, Bordes and Lafille 1962)**
Saint-Cesaire	✓	✓	✗	✗	✓	✓	3	Mercier et al. 1991, Morin 2012, Morin et al. 2005 **(excv. 1976, Leveque and Vandermeersch 1980)**
Saint-Marcel	✗	✗	✗	✗	✗	✗	0	Szmidt et al. 2010 **(excv. 1974, Gilles 1986)**
Salitrena Pecina	✗	✗	✗	✗	✗	✓	1	Marin-Arroyo and Mihailovic 2017 **(excv. 2004)**
San Bernardino	✓	✓	✓	✗	✓	✗	3	Lopez-Garcia et al. 2017 **(Fabiani 1902)**
Sant'Agostino	✗	✗	✗	✗	✓	✗	1	Degano et al. 2019 **(excv. 1947)**
Scladina	✗	✗	✓	✗	✗	✗	1	Pirson et al. 2008 **(excv. 1978, Otte et al. 1983)**
Sesselfelsgrotte	✓	✗	✓	✗	✗	✓	2	Rots 2009 **(Freund 1968)**
Sima de las Palomas	✓	✓	✗	✗	✗	✓	2	Walker et al. 1999, 2008 **(excv. 1994)**
Sopena	✓	✓	✓	✓	✗	✓	4	Pinto-Llona et al. 2012 **(excv. 2002, Pinto-Llona et al. 2005)**
Spy Cave	✗	✗	✓	✗	✗	✗	1	Germonpre et al. 2014 **(excv. 1886, Fraipont and Lohest 1887)**
Stajnia	✗	✗	✗	✗	✗	✗	0	Zarski et al. 2017 **(excv. 2006)**
Susiluola	✗	✓	✓	✗	✓	✗	3	Schulz et al. 2002 **(excv. 1996)**
Tabun	✓	✓	✓	✓	✓	✓	5	Albert et al. 1999, Marin-Arroyo 2013 **(excv. 1927, Garrod and Bate 1937)**
Teixoneres	✓	✓	✓	✗	✗	✓	3	Lopez-Garcia et al. 2012, Rosell et al. 2017, Talamo et al. 2016 **(Serra-Rafols et al. 1957)**

Site	Hearths	Burnt Sediment	Charcoal	Ash	Burnt Lithics	Burnt Bone	Score out of 5	References
Teshik-Tash	✓	✗	✓	✓	✗	✗	2	Nishialki and Aripdjanov 2020, Weidenreich 1945 **(excv. 1938)**
Theopetra	✗	✓	✓	✓	✗	✗	3	Karkanas 2001, Karkanas et al. 1999 **(excv. 1987, Kyparissi-Apostolika 1990)**
Tor Faraj	✓	✗	✓	✓	✓	✓	4	Henry 2017, Henry et al. 1996, Riel-Salvatore et al. 2013 **(excv. 1979)**
Tossal de la Font	✗	✗	✗	✗	✗	✗	0	Olle et al. 2014 **(Gusi et al. 1983)**
Tournal	✗	✗	✗	✗	✗	✓	1	Magniez 2009 **(Tournal 1827)**
Uca Gizli II	✓	✗	✓	✓	✗	✓	3	Mentzer 2011 **(excv. 2005)**
Valdegoba	✗	✗	✗	✗	✗	✗	0	Feranec et al. 2010 **(excv. 1987, Diez et al. 1989)**
Vanguard Cave	✓	✓	✓	✓	✗	✓	4	Barton 2000, Arsuaga et al. 2008, MacPhail and Goldberg 2000, Stringer et al. 1999 **(excv. 1989)**
Vaufrey	✗	✗	✓	✗	✓	✓	3	Courty 2017, Hernandez et al. 2014 **(excv. 1930, Rigaud 1988)**
Veternica	✓	✗	✓	✗	✗	✗	1	Miracle et al. 2010 **(Gorjanovic-Kramberger 1899)**
Vindija	✗	✗	✗	✗	✗	✗	0	Brajkovic and Miracle 2006 **(excv. 1928, Vokovic 1949)**
Wadi Mushkuna	✗	✗	✓	✓	✗	✗	2	Bretzke et al. 2017 **(excv. 2007, Conard et al. 2010)**
Yabroud I	✗	✗	✗	✗	✗	✗	0	Solecki 1986 **(excv. 1930, Rust 1933)**
Zarzamora	✗	✗	✗	✗	✗	✗	0	Sala et al. 2012 **(excv. 1988, Molero et al. 1989)**
Zaskalnaya VI	✓	✓	✓	✓	✗	✓	4	Majkic et al. 2017, Stepanchuk et al. 2015 **(excv. 1969, Kolosov 1973)**
Score out of 169	88	65	107	62	62	99		
Percentage	52.1%	38.5%	63.3%	36.7%	36.7%	58.6%		

Table 3.3: Average number of fire proxies in Middle Palaeolithic cave sites.

Score out of 5	Number of Cave Sites	Percentage	Average Score
0	25	14.79%	2.33
1	32	18.93%	
2	33	19.53%	
3	40	23.67%	
4	19	11.24%	
5	20	11.83%	



Graph 3.1: Plotting the average number of fire proxies in the above sites.

Table 3.4: Middle Palaeolithic open-air sites and their corresponding fire proxies.

Neanderthal Open-Air Sites								
Site	**Hearths**	**Burnt Sediment**	**Charcoal**	**Ash**	**Burnt Lithics**	**Burnt Bone**	**Score out of 5**	**References**
Bagaggera	✓	✓	✓	✗	✓	✗	3	Cremaschi et al. 1990 **(Venzo 1948)**
Berigoule	✓	✓	✗	✗	✓	✗	2	Richter et al. 2007 **(excv. 1988, Brugal et al. 1989)**
Bettencourt	✗	✗	✗	✗	✗	✗	0	Clark 2015 **(excv. 1995)**
Biache Saint-Vaast	✗	✗	✗	✗	✓	✓	2	Bahain et al. 2015 **(excv. 1976, Tuffreau et al. 1982)**
Bojnice III	✓	✗	✓	✗	✗	✓	2	Neruda and Kaminska 2013 **(excv. 1965, Barta 1966)**
Bollschweil	✗	✗	✗	✗	✗	✗	0	Rink et al. 2002 **(excv. 1997, Conard and Kandel 1999)**
Bout-des-Vergnes	✗	✗	✗	✗	✗	✗	0	Courbin et al. 2020 **(excv. 2012)**

Site	**Hearths**	**Burnt Sediment**	**Charcoal**	**Ash**	**Burnt Lithics**	**Burnt Bone**	**Score out of 5**	**References**
Campitello	✗	✗	✗	✗	✗	✗	0	Mazza et al. 2006 **(excv. 2001)**
Canaveral	✓	✗	✗	✗	✓	✗	1	Ortiz Nieto-Marquez and Baena Preysler 2017, Ortiz Nieto-Marquez et al. 2012 **(Baena Preysler et al. 2009)**
Cantalouette	✗	✗	✗	✗	✓	✗	1	Clark 2015 **(Bourguignon et al. 2004)**
Chene Vert	✗	✗	✗	✗	✗	✗	0	Dawson et al. 2012 **(Dawson et al. 2012)**
Combe Brune II	✗	✗	✗	✗	✓	✗	1	Frouin et al. 2014 **(excv. 2003, Bourguignon et al. 2004)**
Combe Capelle Bas	✗	✗	✗	✗	✓	✗	1	Pettitt 1997, Valladas et al. 2003 **(excv. 1926, Peyrony 1934)**
Cuesta de la Bajada	✗	✗	✗	✗	✗	✗	0	Blain et al. 2017, Dominguez-Rodrigo et al. 2015, Santonja et al. 2014 **(excv. 1991, Santonja and Perez-Gonzalez 2001)**
Ein Qashish	✗	✗	✗	✗	✓	✗	1	Friesem et al. 2014 **(excv. 2005, Hovers et al. 2014)**
Erd	✓	✗	✓	✓	✗	✓	3	Daschek and Mester 2020 **(excv. 1961, Hunyadi 1962)**
Far'ah II	✓	✓	✓	✓	✓	✓	5	Friesem et al. 2014, Gilead and Grigson 1984 **(excv. 1972, Price-Williams 1973)**
Fresnoy-au-Val	✗	✗	✗	✗	✗	✗	0	Clark 2015 **(excv. 2002)**
Great Pan Farm	✗	✗	✗	✗	✗	✗	0	Poole 1925 **(excv. 1920)**
Hermies	✗	✗	✗	✗	✗	✗	0	**Vallin et al. 2001**

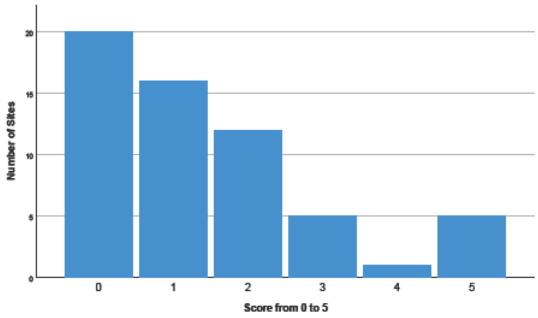
Site	**Hearths**	**Burnt Sediment**	**Charcoal**	**Ash**	**Burnt Lithics**	**Burnt Bone**	**Score out of 5**	**References**
Hummal	✗	✗	✓	✗	✗	✓	2	Hauck 2010 **(excv. 1980, Besancon et al. 1981)**
Inden Altdorf	✓	✗	✓	✗	✗	✗	1	Pawlik and Thissen 2011 **(excv. 2005, Thissen 2007)**
Jiboui	✗	✗	✗	✗	✓	✗	1	Duttine et al. 2005 **(excv. 1997, Tillet et al. 2004)**
Kabazi II	✗	✗	✗	✗	✗	✗	0	Bataille 2010, Uthmeier 2004, Uthmeier and Chabai 2018 **(Formozov 1959)**
Khotylevo I	✓	✓	✓	✗	✗	✗	2	Hein et al. 2020 **(excv. 1960, Zavernyaev 1978)**
Koulichivka	✗	✗	✗	✗	✗	✗	0	Meignen et al. 2004 **(excv. 1998)**
Ksiecia Jozefa	✓	✗	✓	✓	✓	✗	3	Zieva et al. 2008 **(Sitlivy et al. 1999)**
La Cotte de Saint-Brelade	✓	✗	✓	✗	✗	✓	2	Scott 1980, Smith 2015 **(excv. 1961, McBurney and Callow 1971)**
La Folie	✓	✗	✓	✗	✓	✗	2	Clark 2015 **(excv. 2000, Bourguignon et al. 2002)**
Las Callejuelas	✗	✗	✗	✗	✗	✗	0	Domingo et al. 2017 **(excv. 1975, Eisemann et al. 1993)**
Le Prisse	✗	✓	✗	✗	✗	✗	1	Cologne et al. 2015 **(excv. 2010)**
Les Bossats	✓	✓	✓	✓	✓	✓	5	Bodu et al. 2013 **(excv. 2004, Bodu et al. 2011)**
Les Fieux	✗	✗	✗	✗	✗	✓	1	Laroulandie et al. 2016 **(excv. 1967, Champagne et al. 1990)**
Les Forets	✗	✗	✗	✗	✓	✗	1	Duttine et al. 2005 **(Brenet and Foldago 2003)**

Site	**Hearths**	**Burnt Sediment**	**Charcoal**	**Ash**	**Burnt Lithics**	**Burnt Bone**	**Score out of 5**	**References**
Lynford	✗	✗	✗	✗	✗	✗	0	Boismier et al. 2003, Schreve 2006, Smith 2012 **(excv. 2002)**
Maastricht-Belvedere	✓	✗	✓	✗	✓	✗	2	Adler et al. 2003, Loecker et al. 2003, Roebroeks et al. 1997 **(Cremers 1925)**
Mirak	✗	✗	✗	✗	✗	✗	0	Vahdati Nasab et al. 2019 **(excv. 2015)**
Molodova I	✓	✗	✓	✓	✗	✓	3	Demay et al. 2012 **(Morosan 1929)**
Nahal Manahayeem Outlet	✗	✗	✓	✗	✓	✗	2	Biton et al. 2017, Friesem et al. 2014 **(Sharon et al. 2010)**
Nesher Ramla	✓	✓	✓	✓	✓	✓	5	Friesem et al. 2014 **(excv. 2010, Zaidner et al. 2014)**
Neumark Nord II	✗	✗	✓	✗	✓	✓	3	Kuijper 2014 **(excv. 2004)**
Orgnac III	✓	✗	✓	✓	✓	✓	4	Moncel et al. 2012 **(excv. 1959, Combier 1967)**
Piekary IIa	✗	✗	✓	✗	✓	✗	2	Mercier et al. 2003 **(excv. 1967, Morawski 1975)**
Pietraszyn 49a	✗	✗	✗	✗	✗	✗	0	Wisniewski et al. 2019 **(excv. 2015, Wisniewski et al. 2015)**
Plaidter Hummerich	✗	✗	✗	✗	✓	✓	2	Street 2002 **(Bosinski et al. 1983)**
Poggetti Vecchi	✗	✗	✗	✗	✗	✗	0	Aranguren et al. 2018, Benvenuti et al. 2017 **(excv. 2012)**
Pouch-Terrassenpfiler	✗	✗	✗	✗	✓	✗	1	Weiss 2015 **(excv. 2002, Seiler and Runck 2003)**
Preresa	✗	✗	✗	✗	✗	✗	0	Yravedra et al. 2012 **(Arche 1983)**

Site	**Hearths**	**Burnt Sediment**	**Charcoal**	**Ash**	**Burnt Lithics**	**Burnt Bone**	**Score out of 5**	**References**
Quneitra	✗	✗	✗	✗	✓	✗	1	Oron and Goren-Inbar 2014 **(excv. 1971, Belitzky 1990)**
Rosh Ein Mor	✗	✗	✗	✗	✓	✗	1	Friesem et al. 2014, Rink et al. 2003 **(excv. 1969, Marks et al. 1971)**
Saccopastore	✗	✗	✗	✗	✗	✗	0	Marra et al. 2015 **(Sergi 1929)**
Starosele	✓	✗	✗	✗	✓	✓	2	Burke 2000, Marks et al. 1997 **(Formosov 1958)**
Taubach	✓	✓	✓	✓	✓	✓	5	Bratlund 1999, Moncel and Rivals 2011 **(Eichhorn 1909)**
Umm el Tlel	✗	✗	✗	✗	✓	✗	1	Boeda et al. 2008a,b **(excv. 1991, Boeda and Muhesen 1993)**
Velykyi Glybochok	✗	✗	✓	✗	✓	✗	2	Lanczont et al. 2014, Sytnyk et al. 2010 **(excv. 1979, Sytynk and Bogucki 1998)**
Villiers Adam	✗	✗	✗	✗	✗	✗	0	Clark 2015 **(excv. 1996, Locht et al. 2003)**
Wallertheim	✓	✓	✓	✓	✓	✓	5	Adler et al. 2003 **(excv. 1927, Schmidtgen 1932)**
Westeregeln	✗	✗	✗	✗	✗	✓	1	Diedrich 2012 **(Giebel 1850)**
Wrocklaw-Hallera Av.	✗	✗	✗	✗	✗	✗	0	Wisniewski et al. 2011 **(excv. 1991)**
Score out of 59	19	9	21	9	29	17		
Percentage	32.20%	15.25%	35.59%	15.25%	49.15%	28.81%		

Table 3.5: Average numbers of fire proxies in Middle Palaeolithic open-air sites.

Score out of 5	Number of Sites	Percentage	Average Score
0	20	33.90%	1.42
1	16	27.12%	
2	12	20.34%	
3	5	8.47%	
4	1	1.69%	
5	5	8.47%	



Graph 3.2: Plotting the average number of fire proxies in the above sites.

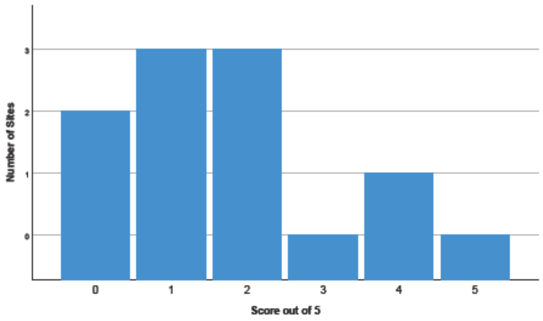
Map 3.1: Locations of Neanderthal cave (black) and open-air (white) sites in this study. Note that open-air sites tend to be more northerly than cave sites.

Table 3.6: Middle-Upper Palaeolithic Transitional Sites and their corresponding fire proxies.

Transitional Cave Sites								
Site	**Hearths**	**Burnt Sediment**	**Charcoal**	**Ash**	**Burnt Lithics**	**Burnt Bone**	**Score out of 5**	**References**
Boker Tachtit	✓	✗	✓	✗	✓	✗	2	Barzilai and Boaretto 2016, Goder-Goldberg et al. 2017 **(Marks 1983)**
Cassenade	✗	✗	✓	✗	✗	✓	2	Discamps et al. 2019 **(excv. 1970)**
Ekain	✗	✗	✗	✗	✗	✓	1	Villaluenga et al. 2012a **(Barandiaran and Altuna 1969)**
Grotta del Cavallo	✓	✓	✗	✗	✗	✗	1	Zanchetta et al. 2018, Zilhao et al. 2015 **(excv. 1961, Palmi di Cesnola 1963)**
Grotte des Fees de Chatelperron	✓	✓	✗	✗	✗	✓	2	Zilhao et al. 2008 **(Bailleau 1869)**
Jerf al-Ajla	✗	✓	✓	✓	✓	✗	4	Richter et al. 2001 **(excv. 1955, Coon 1956)**
Labeko Koba	✗	✗	✗	✗	✗	✗	0	Villaluenga et al. 2012a **(excv. 1987, Arrizabalaga and Altuna 2000)**
Nietoperzowa	✓	✗	✓	✗	✗	✗	1	Krajcarz et al. 2018 **(excv. 1854, Romer 1875)**
Roc-de-Combe	✗	✗	✗	✗	✗	✗	0	Grayson and Delpech 2008 **(excv. 1959, Bordes and Labrot 1967)**
Score out of 9	4	3	4	1	2	3		
Percentage	44.44%	33.33%	44.44%	11.11%	22.22%	33.33%		

Table 3.7: Average number of fire proxies in Transitional sites.

Score out of 5	Number of Cave Sites	Percentage	Average Score
0	2	22.22%	1.44
1	3	33.33%	
2	3	33.33%	
3	0	0.00%	
4	1	11.11%	
5	0	0.00%	



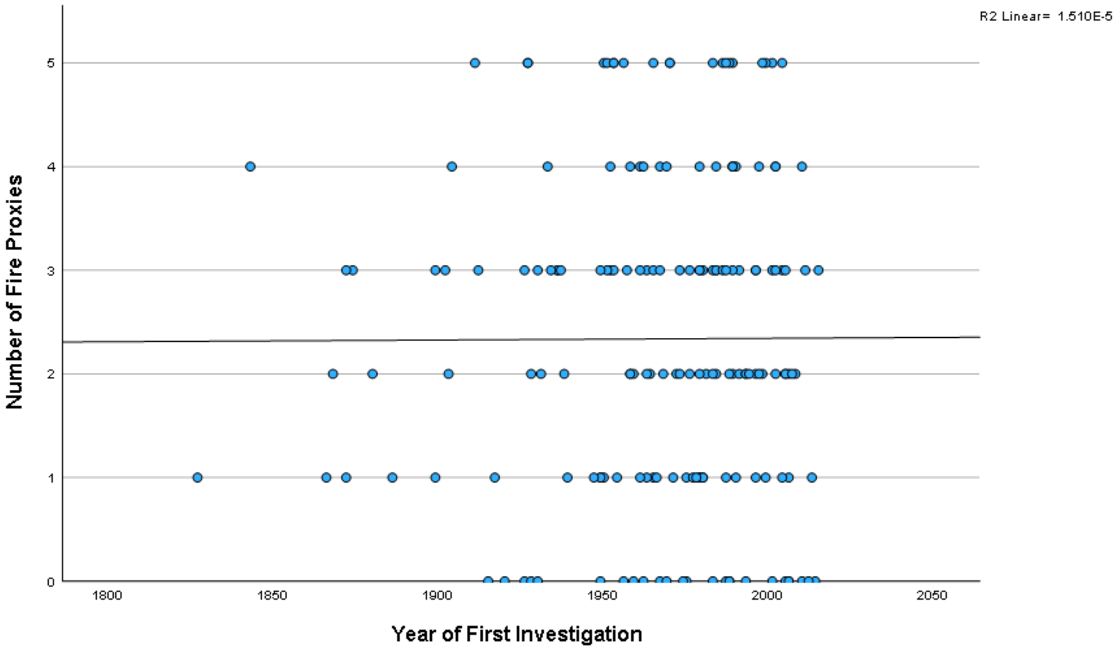
Graph 3.3: Plotting the average number of fire proxies in the above sites.

Map 3.2: Location of Transitional Cave sites in this study.

III. Discussion.

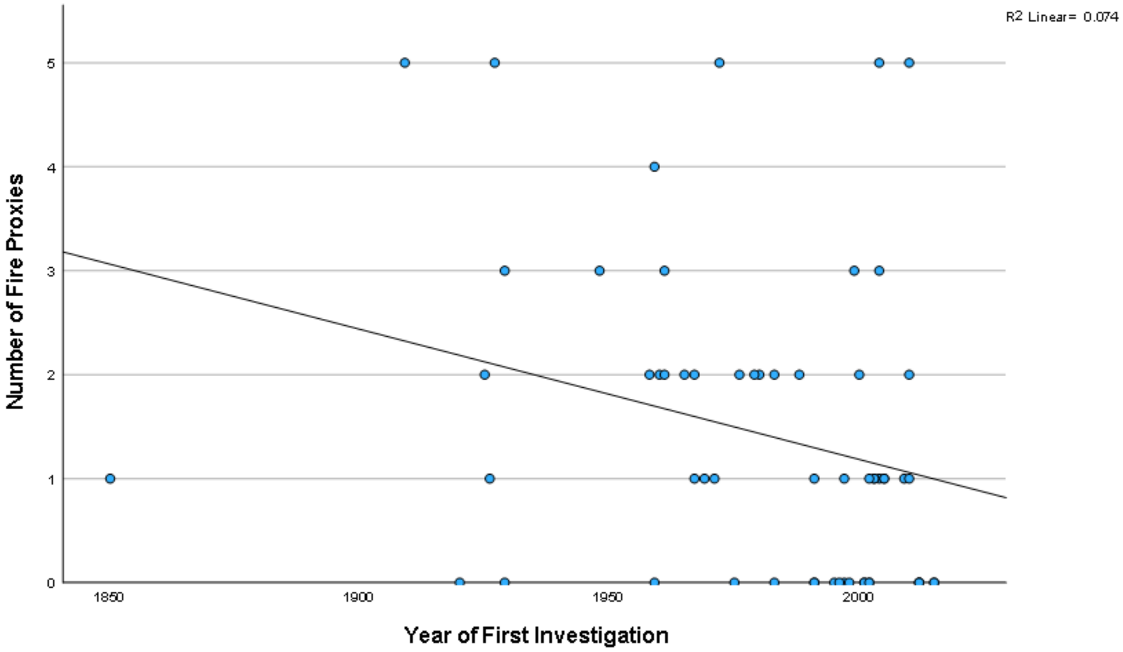
In theory, sheltered caves should preserve in-situ archaeology (especially fragile elements) better; in-situ hearths and fragile elements like rubified sediment, charcoal and ash will be more prevalent in caves due to taphonomic biases alone. However, less friable elements like burnt lithics and burnt bone may be equally frequent in both site types – assuming comparable fire frequencies between the two. Open-air sites are frequently discovered in modern development rescue excavations, whereas cave sites were often excavated c.1920s-1960s, and may have been subsequently re-excavated more recently (e.g. the ongoing Shanidar project). This introduces issues in both cases. Cave sites may have been poorly-excavated initially, missing key archaeological elements (e.g. Brno-Bohunice, containing transitional Bohunician industries, was not sieved on initial excavation – Tostevin and Skrdla 2006); however, conversely, they have been long-known, with many associated papers, may have been subject to alternative fire-detecting methods, and may have been recently re-excavated. Modern open-air excavations have been rigorously excavated recently; however a) being development rather than research digs, they may not have been excavated in such detail, and b) being recent, many have not analysed/published their finds yet. Thus both site types, based on modes and eras of excavation, have potential associated research biases.

I plotted the number of fire proxies (theoretically corresponding to intensity of fire use) against the date of first excavation for each site. Although this in not an infallible metric, as even a site discovered in 1850 may only have been excavated for three years, versus one discovered in 1990 being excavated for twenty, nonetheless sites discovered longer ago tend to have been excavated more. Graph 3.4 shows that, for cave sites, there is absolutely no change through time in detecting fire use (R2 = 1.51e-5) and that a bias is unlikely to exist there.



Graph 3.4: A graph showing that the date of first excavation of a Middle Palaeolithic cave site has no impact on how many fire proxies are discovered (R2 = 1.510e-5). This suggests that earlier sites, with more rudimentary excavating techniques, may have been investigating caves with stronger anthropogenic signatures.

However, open-air sites show strong declines in detecting fire use, with recently-discovered sites showing many fewer fire proxies than those discovered longer ago (Graph 3.5, although statistically insignificant as R2 = 0.07). Consequently, when the two site types are combined, there is a moderate decline in detecting fire use (Appendix Seven, Graph A25). Open-air sites are harder to detect than caves, which are obvious places to look for archaeology; older excavations would target caves, finding both rich and more ephemeral sites. However, in the open air, older excavations would only find and target richer sites denoted by lithic surface scatters. The open-air ephemeral sites are only being found more recently, through development or more careful surveying; these more ephemeral sites consequently show less fire use, as they were less intensively occupied and less fire was used there originally.



Graph 3.5: A graph showing that open-air Middle Palaeolithic sites excavated more recently show fewer fire signatures, although this correlation is weak (R2 = 0.074). This suggests that modern sites being excavated show more ephemeral archaeology, and those with more fire originally happened to be excavated earlier last century.

The average score for Neanderthal caves (2.33), open-air Neanderthal sites (1.42), and Transitional sites (1.44) proportionally mirrors hearth frequency: in 52.07% of Neanderthal caves, 32.20% of open-air Neanderthal sites, and 44.44% of Transitional sites. Most importantly, most sites evidence *some* fire use; 85.21% of Neanderthal cave sites, and 66.1% of open-air sites, for overall fire being found in 80.27% of Neanderthal sites. Only 45 are completely fireless. This strongly indicates that many Neanderthals encountered and used fire at least occasionally. Many sites are also occupied only seasonally (e.g. Shanidar having autumnal and spring occupations with pistachio nuts found – Hunt pers. comms.), and fireless sites may just represent fireless *seasons* of fire-using groups.

A bias against detecting Transitional fire use is that such layers mostly only span c.5,000 years, compared to >10,000 years of Mousterian occupations. Transitional sites may display less fire than Classic Mousterian sites for this reason alone. However, many long-term Mousterian sites often have long sterile layers (often during tough MIS 4 glacial periods as at Shanidar Cave – pers obvs) and actual occupation durations may be more similar. Transitional sites may be archaeologically-richer and climatically-favourable, showing more fire use for that reason. The paucity of Transitional sites also makes deciphering this result difficult. As expected, short-sequence Transitional sites showed consistently lower traces of fire than Classic Neanderthal cave sites; less than half of every fire proxy, except burnt sediment which shows similar proportions (Neanderthal caves = 37.87%, Transitional caves = 33.33%). However, given the few Transitional sites studied, individual taphonomies and site publication histories particularly affect these results. Chatelperron and Boker Tachtit are well-known, but others such as Ekain and Jerf al-Ajla are poorly studied. Furthermore, not being Classical Neanderthal sites, they are less studied for fire use specifically, as fire is no longer seen as a novel technology, and when found, cannot always be definitively attributed to a particular species. Compared to Neanderthal open-air sites, Transitional sites have similar fire frequencies, and higher proportions of burnt sediment, suggesting that fire use remained important.

Table 3.8: Comparing fire proxies between Middle Palaeolithic cave and open-air sites. Most are much more common in caves than open-air sites; the only exception is burnt lithics, where the trend is reversed. This information is presented graphically in Graph A33, p.402.

Fire Proxy	**Cave Sites**	**Open-Air Sites**
Hearths	50.89%	32.20%
Burnt Sediment	37.87%	15.25%
Charcoal	62.72%	35.59%
Ash	36.09%	15.25%
Burnt Lithics	36.69%	49.15%
Burnt Bone	58.58%	28.81%

Comparing Mousterian cave and open-air sites in Table 3.8 above presents stark contrasts. Aside from burnt lithics, which are common in open-air sites, every other fire proxy is almost twice as common in caves as in open-air sites. Two original models explain these results; either taphonomic differences have disguised similar fire frequencies, or caves were more frequent fire locations than open-air sites.

In the first scenario, open-air sites originally had as frequent fire events as cave sites. Neanderthals seasonally or annually alternated between cave and open-air sites, creating identical fires in each. Fires would have been situated near cave entrances to minimise cave smokiness and maximise airflow, and centrally in open-air sites. Large, communal fires could signal Neanderthal presence; small personal hearths may have been smaller and closer to cave walls to avoid unwanted attention or windy situations. However, subsequent taphonomic disturbance from faunal, aeolian and fluvial sources caused open-air sites to become more disturbed than caves; trampling and other anthropogenic disturbance is common in both (Karkanas et al. 2021). This scenario is supported by comparable levels of durable burnt lithics; friable charcoal and ash remain in caves, being washed away in open-air sites while durable elements remain in both. This is further supported by the prevalence of discrete hearth features, indicating undisturbed sediments, found in 50.89% of caves, but only 32.2% of open-air sites. However, caves still contain more durable burnt bone, despite similar overall prevalences of bone in both site types in the site reports. If Neanderthals were only at either open-air or cave sites each day (barring occasional temporary hunting camps alongside cave base camps, or vice-versa with lithic gathering camps in caves), Neanderthals then may have only cooked meat in secure caves away from predators, eating it raw outside. This may partially explain why Neanderthals evidencing cooking are not dietarily-obligate fire-users.

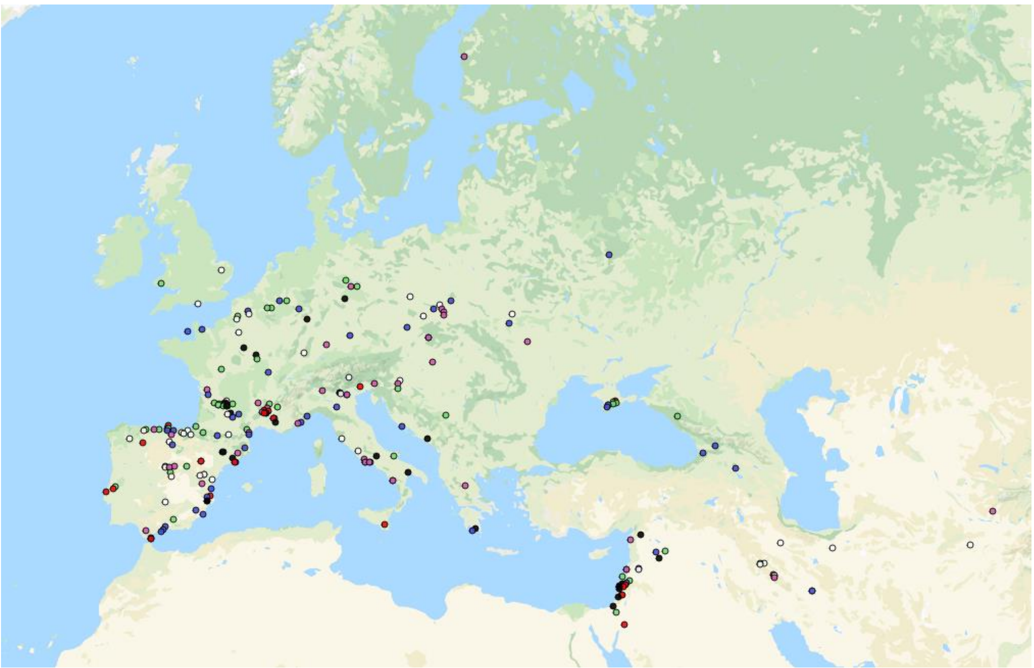
The other scenario is where fire use was much more common in caves than in open-air sites, with minimal differential taphonomic preservation. This is the case for most fire proxies, as proportions remain roughly the same, with almost twice as many examples in caves. The exception is burnt lithics (found in 49.15% of open-air sites but only 36.69% of caves). Were open-air sites traditional knapping and heat-treating areas and caves not? Examples of conjoinable knapping fragments are frequently found in both site types. Burnt lithics are specifically recorded for TL-dating older sites, and open-air sites tend to be older than cave sites (see p.100). Alternatively, have burnt lithics in caves been removed somehow, with those in open-air sites remaining at near-original levels? Neanderthal cave sites were sometimes maintained and cleared (e.g. Kebara – Speth 2006). However, cleaning indiscriminately between burnt and unburnt lithics would not explain the data and it is hard to envisage cleaning or taphonomic processes targeting only burnt lithics. If lithics were *unintentionally* heated in sub-hearth substrates rather than in the flames, substrate differences may explain this difference. However, fire-using Iberian sites show many substrate types (see p.98), suggesting that no typical ‘cave’ substrates are comparable to typical ‘open air’ substrates.

In this scenario, Neanderthals cooked more and had generally more fire in caves. This may partially have been through necessity; darker caves necessitated more fire to extend working days. Caves may also have been (potential) homes of more dangerous predators than open-air sites, requiring more hearths to advertise Neanderthal presence to predators or other hominin groups. If caves were more valuable shelter resources, or if cave signals were more visible in the landscape (coming from higher-up, barren cliff faces), more fires would be expected here. Fire is also a cleansing agent, removing insects, old bedding or potentially bacteria-ridden dung. Neanderthals may have only used fire to cleanse caves at the start and end of occupation periods. This explains burnt lithics and bone as cleared waste rather than technological by-products. In open air sites however, Neanderthals may not have done this, possibly because of shorter occupation periods or faster plant regrowth making fire-clearance less worthwhile. Furthermore, cave sites are immutable site locations – Neanderthals may have used nearby but different open-air locations each visit, making each open-air site far more ephemeral. Fewer fire proxies would remain from shorter visits, despite similar *frequencies* of use.

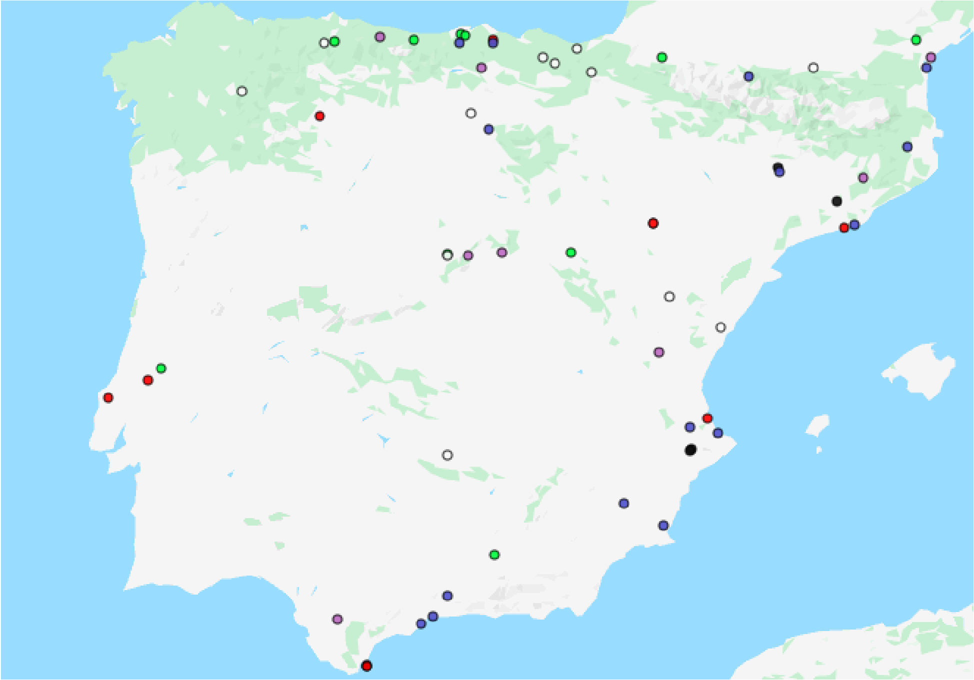
Seasonality may also have affected fire use – July and August have most lightning strikes to ignite wildfires, and fuel is naturally driest then. Cold winters require most fire for warmth, but snowdrifts conceal most of the deadwood. Teixoneres Cave Level IIIa shows occupation during all seasons, whilst IIIb shows habitation only during summer and winter (Sanchez-Hernandez et al. 2014), and Shanidar Cave shows spring and autumn occupation (determined by the presence of ripened pistachio nuts – Barker pers. comms.). Obviously, seasonal occupation varied from site to site and region to region; if, however, Neanderthals occupied caves in seasons when fire was easier to kindle and fuel, or was more necessary for survival, then fire use would have been much higher in caves. Finally, an implausible possibility is that cave-dwelling and open-air Neanderthals were entirely different populations with little technological communication or sharing. Cave-dwelling Neanderthals lived only in caves, lighting fires in each, whilst open-air Neanderthals were fireless, either through ignorance, or frequent site relocations causing cost-benefit ratios to be too high. This dichotomy could have arisen from different subsistence strategies, if open-air Neanderthals followed prey herd movements whilst cave-dwellers focused on local prey procurement in resource-rich areas. However, this theory is not yet evidenced; lithic refitting studies between different site types to determine individual movements could strengthen or disprove this model.

III.I: Regional Trends.

When looking at patterns across Europe and the Near East, sites can be grouped thus, according to the number of fire criteria visible in each:

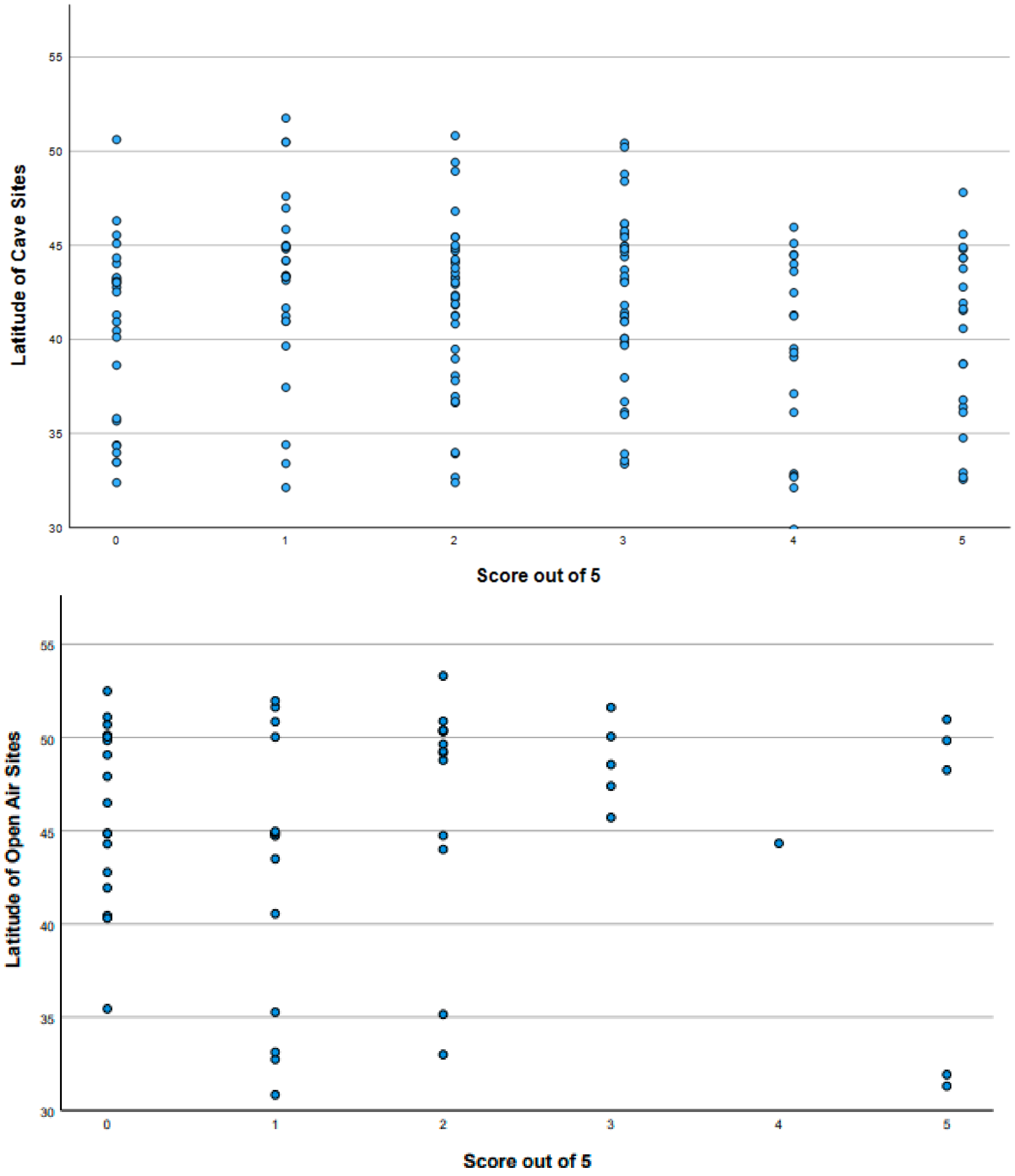


Map 3.3: Neanderthal cave and open-air sites correlated with the number of fire proxies (charcoal, ash, burnt sediment, burnt lithics, burnt bone) in them; 0 proxies (white), 1 proxy (green), 2 proxies (blue), 3 proxies (pink), 4 proxies (red), 5 proxies (black).



Map 3.4: The same map as Map 3.3, but highlighting the Iberian Peninsula.

Fire use and geographical location minimally correlate. However, coastal Israeli sites show more proxies than other inland Near Eastern sites. This however is just a byproduct of preferential scientific sampling, as well-known Israeli sites (e.g. Kebara) are better-studied than more inaccessible inland sites and thus naturally provide more proxies. Map 3 also suggests slight decreases in numbers of fire proxies in more northerly sites. However, Graph 3.6 below does not support this, as there are more open-air sites at high latitudes and less fire use in open-air sites, but no latitude dependence within either category:



Graph 3.6: The Latitude of Cave Sites (above) and Open-Air Sites (below) correlated with the Score out of 5. Both appear uncorrelated.

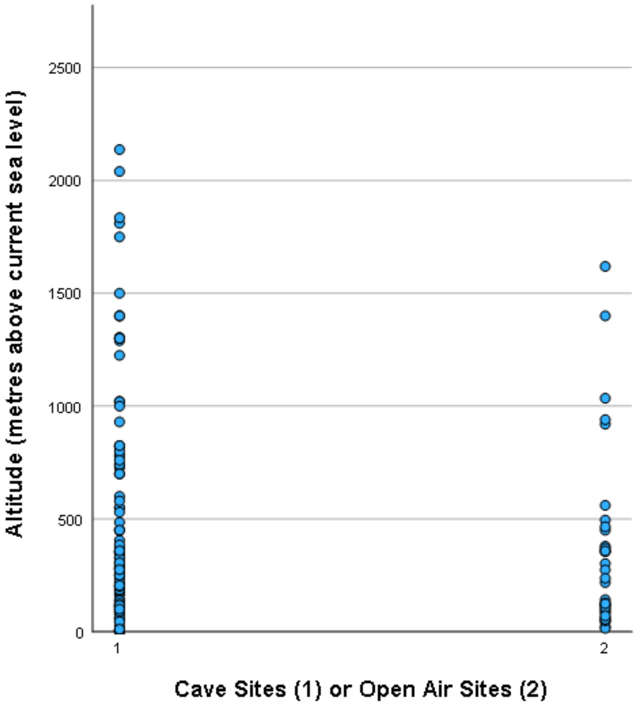
Table 3.9: Comparing fire frequency and latitudes of Middle Palaeolithic cave and open-air sites.

Score out of 5	**Mean Latitude (N)**		
	Cave Sites	**Open-Air Sites**	**All Classic Neanderthal Sites**
0	40.55	45.95	42.78
1	43.13	43.094	43.12
2	41.63	46.84	42.96
3	42.81	48.66	43.52
4	39.16	44.32	39.42
5	40.17	42.45	40.61

These results suggest that latitude minimally affect Neanderthal fire frequency (also see Graph A34, p.403). This interestingly does not suggest that Neanderthal fire was limited by fuel/ignition availability, or that northwards expansion relied on fire. In the former theory, northern tundra-type sites had less nearby dry deadwood and fewer lightning strikes than southern Mediterranean-type climates, causing fewer wildfires for Neanderthals to exploit; thus southerly sites would show more proxies. The latter theory is that fire is more valuable further north, for warmth and light in longer, colder winter evenings. Additional foraging overcame fuel shortages, and more proxies would be expected in more northern sites. The fact that neither model predominates suggests either that neither factor was strong enough to influence Middle Palaeolithic fire use, or that both factors were equally strong, counterbalancing each other. Southern Neanderthals, needing less fire, had ample fuelwood available and utilised it, and northern Neanderthals, needing more fire but having less fuelwood, foraged harder to overcome this disadvantage.

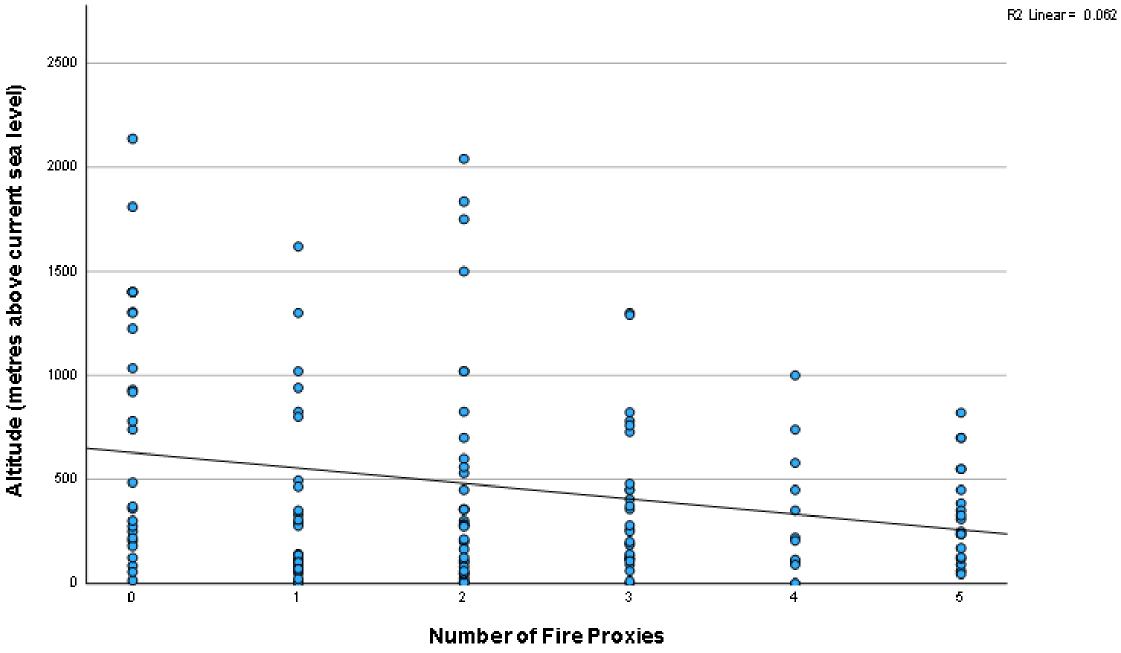
Importantly however, latitude never perfectly correlates with climate and temperature, as glacial southern sites were much harsher than temperate northern sites. Finer-scale layer-by-layer fire data, correlated with climate, would resolve this; however this has its own cost. Although some palaeoenvironmental proxies are independent of fire use (micromammals, pollen etc.), much depends on charcoal to determine paleoarboreal composition. Those sites preserving less fire use have less environmental information; also because they were occupied less intensively, less palaeoenvironmental research has been undertaken as they are deemed less important. Furthermore, different sites naturally suffer different degrees of taphonomic disturbance. This same disturbance which destroys fire proxies also destroys other environmental proxies at similar rates, through mechanical, biological and chemical mechanisms. Therefore disturbed sites showing low rates of fire proxy survival also have little information to reconstruct palaeoenvironments from. Finally, charcoal used to reconstruct arboreal compositions frequently supposes the Principle of Least Effort (PoLE) in wood gathering (see Chapter Five, p.132 for details). This thesis tests whether the PoLE is appropriate for use in Neanderthal contexts, therefore it cannot automatically be assumed that charcoal records represent palaeoenvironmental composition (see Chapter Seven).

However, as an alternative, I plotted fire proxies against altitude for both site types. This is altitude above *current* sea level, which is different to Middle Palaeolithic sea level. These varied greatly over time, particularly between glacial and interglacial periods. Mean sea levels varied between c.15m above current levels to as low as 130m below current levels (all reviewed in Benjamin et al. 2017). This has of course destroyed almost all sites below current sea levels, creating an artificial dearth of sites close to the glacial sea levels. However, there is still a small difference in mean altitudes of open-air and cave sites (Graph 3.7). Cave sites have a mean height of 492m asl, and open-air sites have a mean of 358m asl. However, when put through Welch's T-test (see Chapter Five, p.145 for details), this result was statistically insignificant (p = 0.117). It is notable however that the very highest sites are mostly caves; above 1500m, there is only one open-air site but six caves. This is as expected, as a cave's natural shelter would be especially valuable at high altitudes.



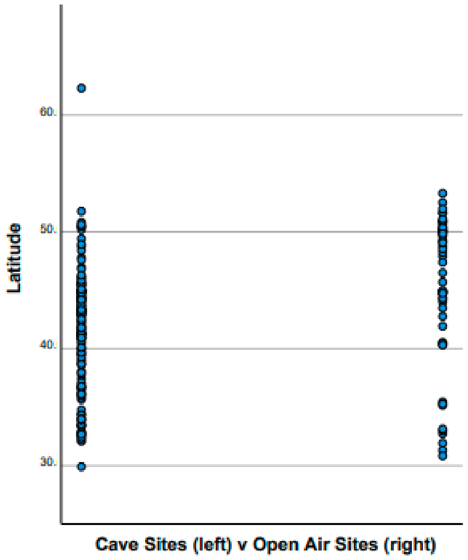
Graph 3.7: A graph showing that although there were more very high-altitude (over 1500m asl) cave sites, the mean altitudes for cave and open-air Neanderthal sites were not dissimilar.

When plotting number of fire proxies against altitude, a trend is shown where more fire proxies are found at lower altitudes (Graph 3.8, and Graphs A26-A27 in Appendix Seven). Whilst this trend is statistically insignificant (R2 = 0.062), it does suggest that fuelwood availability, which is altitude-dependent and more abundant at lower altitudes, had some effect on Neanderthal fire frequency.

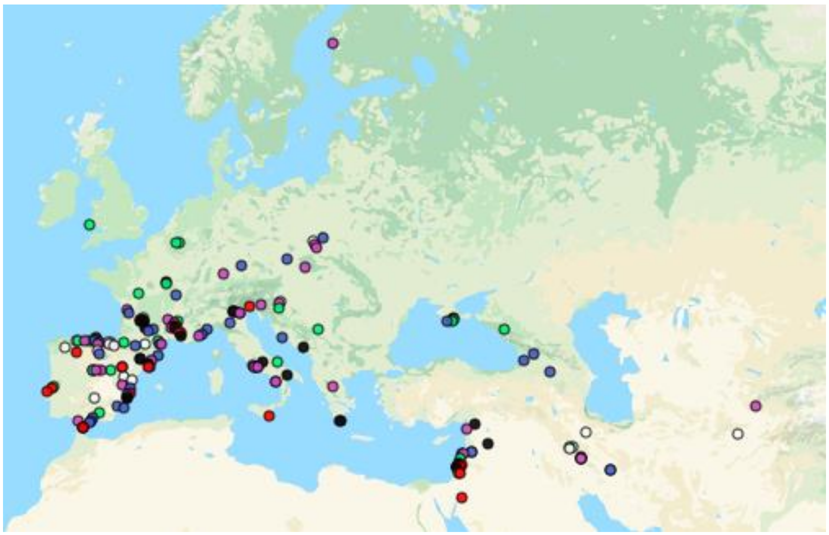


Graph 3.8: A graph showing that more fire proxies are found at lower-altitude sites (R2 = 0.062). As this is likely to correspond with fuelwood availability, it may suggest that high-altitude sites did not use fire because of a lack of fuelwood, rather than because of a lack of technological proficiency.

More northerly sites tend to be open-air rather than caves (due to the plethora of the former in northern France and Germany – Map 3.1); given that open-air and cave sites have *inherent* differences in fire regimes irrespective of latitude, this may account for some variation in fire use between open-air and cave sites. The mean latitude for cave sites is 41.48N (42.48N is the median), and the open air site mean is 45.28N (median: 46.49N); the 420km N-S difference in the Means suggests that this may be an important factor. More northerly open-air sites may have been limited in fire use by latitude rather than open-air natures, if there was insufficient fuel; and more southerly cave sites may have had more fire because of fuel abundance, rather than because fire remains were better protected.



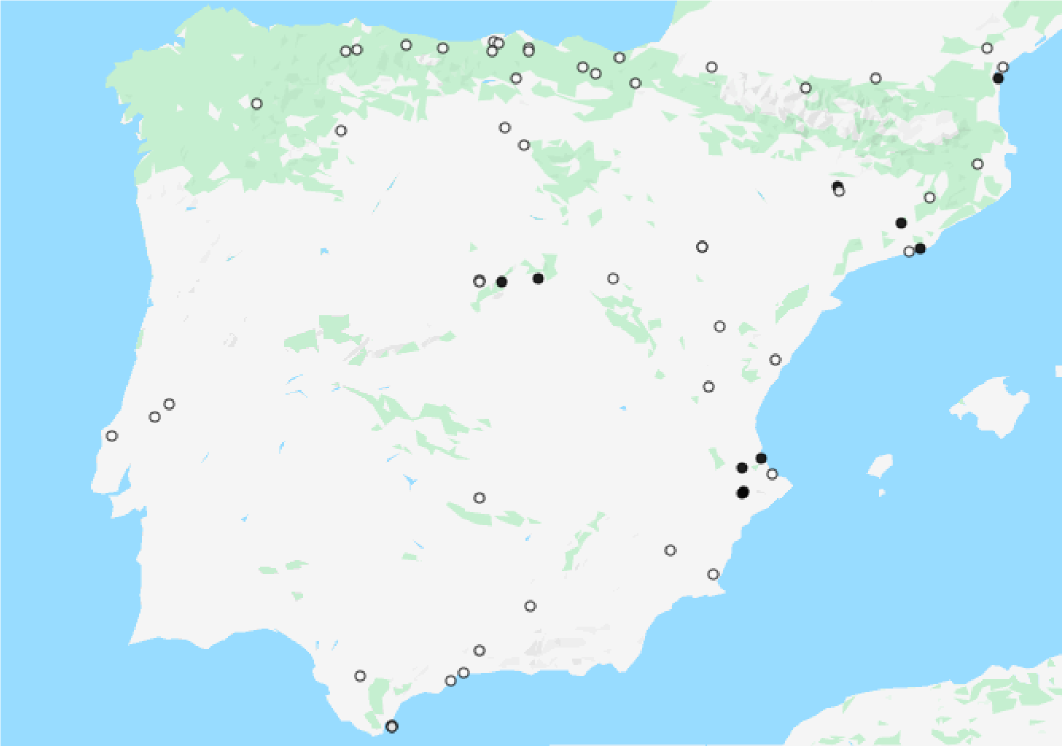
Graph 3.9: Latitudes of cave and open-air Neanderthal sites; despite overlapping distributions, open-air sites are slightly more northerly; their two peaks correspond to those northern European and Near Eastern sites.



Map 3.5: Neanderthal cave site distribution across Europe, coloured by the number of fire proxies; 0 proxies (white), 1 proxy (green), 2 proxies (blue), 3 proxies (pink), 4 proxies (red), 5 proxies (black).

Map 3.5, above, shows fire proxy distributions of cave sites only. In this however, the same lack of correlation with latitude appears. The trend in the Near East for more westerly sites to score higher still remains; interestingly here however, aside from the Near East, the only fireless sites appear in Iberia, an area otherwise characterised with sites with many proxies. Looking at Map 4, a close-up of Iberia alone, this latitudinal trend does not appear. This may be because Iberia is not large enough for temperature gradients to create different ecosystems in north-south patterns. Instead, local climates may have been patchier, with random distribution of proxies either representing that, or the fact that fire here was less climate- and more culture-dependent. Alternatively, Iberia is highly-investigated, including many ephemerally-occupied sites which are mostly carnivore dens; these sites may not have been investigated in other regions, and their inclusion here drives down proportions of fire-using sites.

Looking at most individual proxies, and mapping them across their spatial distribution, I generally found no notable trends (see Appendix One). However, when looking at burnt lithics, they appeared grouped in clusters, which seems more apparent in Iberia alone (see Map 3.6).



Map 3.6: Neanderthal sites in Iberia, highlighting those with burnt lithics (black) and those without (white).

Sites with burnt lithics are concentrated in more restricted areas than those without. To analyse this, I constructed a Minimum Spanning Tree (MST) to determine clustering in Iberia (methodology following Graham and Hell 1985). Doing so for all Europe would introduce areas where seas separates sites/countries, creating artificially-large distances without data points. The total MST for burnt lithic sites is 1545km; with 9 segments between the 10 points, the average distance is 172km. To compare this clustering with any other 10 sites without burnt lithics, I selected repeated random subsamples of 10 sites without burnt lithics from this map. The mean of this MST was 2053km, with 2/3 of the data lying between 1700 and 2200km. The average edge length here was 228km, much longer than the burnt samples. This suggests that sites with this proxy were grouped (most in the south-east, and none in the north-west).

Furthermore, sites with burnt lithics appear more likely to have other nearby sites with burnt lithics, as seen in Map 6. If 10/60 Iberian sites have burnt lithics, a random distribution would suggest that a site's nearest and second-nearest neighbour would each have a 1/6 chance of having burnt lithics. In our data, from the 10 sites with burnt lithics, there are 9 first or second nearest neighbours also with burnt lithics, a fraction of 9/20 (calculating 10 nearest neighbours and 10 second-nearest neighbours). In order to calculate the probability of r instances of burnt lithic presence from n selections, I use the equation:

$$prob(r|n) = C(n,r) \times q^r \times (1-q)^{(n-r)}$$

$$\text{where} \quad C(n,r) = \frac{n!}{(r!(n-r)!)}$$

n = number of selections

r = number of occasions

q = probability of a burnt lithic in a single selection

Using n=20, r9 and q = 1/6, the probability of having 9+ burnt sites among the 20 first and second nearest neighbours, under a random distribution is 0.3% (p = 0.003), a highly significant (3 result. Therefore it is extremely unlikely that this association between incidences of burnt lithics in adjoining sites is compatible with a random distribution of this proxy.

The explanation for this phenomenon is twofold; it could represent cultural clustering, either single groups occupying multiple sites seasonally, or transmission between multiple groups. This 'cultural' effect could either be for deliberate lithic heat-treatment, increased knapping close to hearths, or hotter fires (thus increasingly burnt substrate lithics). On the other hand, this clustering could simply be due to local geographical/geological effects; especially stony or heat-transmitting substrates would increase burning of buried stones, or some abundant local fuel unintentionally caused extra-hot fires which accidentally burnt more buried lithics. From published papers, I studied the substrate compositions of all fire-bearing layers in Iberia; the only sites I could not find detailed results for were Covalejos and Llonin caves. For the rest however, the substrate compositions varied immensely, but contained similar averages (see Table 3.10 beneath). The most notable difference was sandy sediments, which were more common in sites with burnt lithics. As sand is frequently used as a heat-transmitting medium, it may be that sandy substrates transmit more heat from hearths, and therefore burn more lithics buried within it.

Table 3.10: A comparison of substrate types of Iberian fire-using sites with and without burnt lithics. Most of these values are extremely similar; sites with burnt lithics tend to be sandier, and sites without tend to have more loamy soils, which may have inhibited heat transfer.

Substrate Type	Percent of Iberian Sites with Burnt Lithics with this Substrate	Percentage of Other Fire-Using Sites in Iberia with this Substrate
Sand	81.82%	54.84%
Clay	72.73%	74.19%
Silt	54.55%	51.61%
Gravel	36.36%	22.58%
Loam	0%	9.68%

III.II: Temporal trends.

Of those studies, open-air sites are marginally older than caves on average (means of 106.7 and 73.9ka respectively). However, dating is by no means precise, and error ranges tend to increase with age for many reasons. Firstly, more precise radiocarbon dating is only applicable up to c.50ka, as older samples generally have insufficient ^{14}C for this procedure. This limits this dating to sites c.0-50ka, and older ones rely on techniques such as thermoluminescence or argon-argon dating. Sites on the margin of 50ka generally have multiple dating methods applied to them, both for their own accuracy and to test the dating procedures themselves. Sites have a variety of date ranges; the results are broken down in Table 3.11 below, and in Graph A35, p.403:

Table 3.11: Comparing dating ranges (all dating methods) for Middle Palaeolithic cave and open-air sites. These are the ranges of the means of each dated object/sediment (excluding analytical uncertainty), naturally excluding those that the authors themselves have excluded as being outside plausible date ranges. In fire-using sites, I include all dated fire-using levels, which of course are only a subset of the total. With fireless sites, I include all fireless Middle Palaeolithic levels. Thus fire-using sites represent fewer layers than fireless sites, and appear to be occupied for shorter timescales, irrespective of the site's overall length of occupation

Date Ranges	**Number of Cave Sites**	**Number of Open-Air Sites**	**Total Number of Sites**
Single Date	22 (14.97%)	16 (31.37%)	38 (19.19%)
<5kyr	14 (9.52%)	3 (5.88%)	17 (8.59%)
5-10kyr	27 (18.37%)	5 (9.80%)	32 (16.16%)
11-25kyr	43 (29.25%)	10 (19.61%)	53 (26.77%)
26-50kyr	18 (12.24%)	4 (7.84%)	22 (11.11%)
50-100kyr	9 (6.12%)	10 (19.61%)	19 (9.60%)
>100kyr	14 (9.52%)	3 (5.88%)	17 (8.59%)

Single dates may (ideally) perfectly represent single short occupation periods, or represent the only date currently available for particular levels or sites. Conversely, wider date ranges may suggest longer occupation periods, or represent variable interpretations of single occupations, based on unreliable dating proxies. It is impossible to say that sites with either shorter or longer timescales are more- or less-reliably dated, as this depends on so many variables.

Table 3.12: Comparing undated Middle Palaeolithic cave and open-air sites and number of fire proxies. This is also presented in Graph A36, p.404.

Number of Fire Proxies	**% of undated cave sites**	**% of undated open-air sites**	**% of total undated sites**
0	36%	25%	31.1%
1	22.2%	18.8%	20.9%
2	5.9%	0%	4.3%
3	10.5%	20%	11.6%
4	5.3%	0%	5.0%
5	15%	20%	16%

Table 3.12 above shows the proportion of undated sites with 0-5 fire proxies. As expected, sites with 0 fire proxies are the least dated. This is partly because they often have smaller or worse-preserved assemblages, and there is less academic interest in them; or more probably because the fire proxies *themselves* act as dating proxies (especially charcoal and burnt lithics), and so these proxies will be noted as part of site chronologies rather than site assemblages.

Cave sites however tend to be better-dated than open-air sites in terms of range and accuracy of dates within a single site. Single dates often represent the only dating available for open-air sites with short stratigraphies, and otherwise the ranges tend to be longer than for cave sites. Table 3.13 (below) indicates that Neanderthals increasingly moved to more cave occupations and fewer open-air sites over time. This may indicate new subsistence models around intensively-used seasonal sites. If cave occupation dates are generally younger however and within the radiocarbon threshold (<50ka), they will more often be able to be radiocarbon-dated too, restricting them to a range of c.50-40ka. Older open-air occupations have potentials for much longer TL or OSL sequences. Cave stratigraphies are often particularly complex, requiring many dates to understand layer boundaries and sedimentation rates. The particular interest in 'last Neanderthals' also means that sites c.40ka will be particularly strongly-dated.

When looking at fire use in these sites against time, both site types show statistically-insignificant changes of fire use throughout time. Using Pearson's two-tailed significance, R remains below 0.05, (p = 0.568 and p = 0.774 for cave and open-air sites respectively). When looking at the sites together, the R-trends likewise remained below 0.05 (non-significant as p = 0.751). Given that archaeology is a record of loss, earlier sites would preserve less fire than later ones if fire use remain constant throughout time. The fact that they do not either suggests that fire remains are less friable than certain other archaeological materials, or that fire use marginally *declined* through time, but was recognised more in later sites. The most friable fire proxy, complete hearths, might become more common through time from taphonomic concerns alone, with burnt flint and charcoal more commonly noted in older and younger sites respectively due to being used as dating proxies. However, no such trends were noted:

Table 3.13: Comparing the ages of Middle Palaeolithic cave and open-air sites; also mapped graphically in Graphs A31 and A32 in Appendix Seven.

Site Type	**Average Age with charcoal (ka)**	**Average age with burnt flint (ka)**	**Average age with hearths (ka)**	**Average Age (ka)**
Cave	72.1	86.2	74.2	73.9
Open Air	115.2	105.0	110.5	106.7

Although caves with burnt flints showed a small age increase compared to the average cave site age, this 16.6% difference was the largest of any, suggesting that sampling bias was not responsible for any age trends of these proxies. Given radiocarbon's cut-off point is c.50-60ka, we would expect that if sampling bias was significant (charcoal and burnt lithics being only noted and collected for use as respective dating proxies), most charcoal would be younger than this date, and most burnt flint older. If charcoal and burnt lithics were instead noted as fire proxies, both proxies would probably have more examples over this date, as there are simply more older sites investigated. Whilst 59.8% of cave charcoal was <60ka, suggesting possible bias, only 35% of open-air charcoal was; burnt flint >60ka was found at 54.4% of caves and 65.5% of open-air sites, but this is consistent with either theory.

These individual proxy dates being so close to the average dates for each site type suggests that time has not significantly affected the survival of these fire materials. Furthermore, the data is not strong enough to state whether any age-related patterning exists (although see Table 3.14 below, and Graph A37, p.404). It certainly does not strongly suggest that continental-scale Neanderthal fire regimes fluctuate particularly through time. However this analysis is insufficiently fine-scale to detect cultural responses to glacial cycles.

Table 3.14: Comparing fire frequency and age of Middle Palaeolithic cave and open-air sites; no trends are apparent. This is also presented on Graph A37, p.404.

Number of Proxies noted	**Average Cave Site Age (ka)**	**Average Open Air Site Age (ka)**	**Average Combined Age (ka)**
0	78.2	111.2	94.2
1	63.1	87.6	71.1
2	70.7	121.1	85.3
3	81.5	68.4	80.1
4	80.5	331	93.7
5	75.0	82.9	76.5

IV: Conclusion.

This chapter has highlighted the general presence of fire in Neanderthal sites across long spatio-temporal scales. Although compared to ubiquitous modern human fire, 80.27% of sites (85.21% of cave sites) having fire is not high, it does imply that pyrotechnology was common to Neanderthals (especially given that taphonomic processes mean that these percentages are absolute lower limits). This chapter highlights overall scales of Neanderthal fire; it does not detail individual sites' fire histories, as has been attempted at Pech de l'Aze. Thus it cannot reveal details of particular Neanderthal lives. I investigate an entire species' technology rather than a single group's, which may differ immensely. The advantage of such studies is precisely that it is not confined to single groups, whose behaviours may not represent general populations, but gives general baselines from which to study specific areas.

The second finding has been that of a notable difference in fire proxies between caves and open-air sites. Whilst this was partially expected due to the obvious protection of cave roofs, the difference was unexpectedly high, approaching 50% more of particular proxies in caves. A relative difference between "friable" and "durable" proxies was expected. Friable proxies would benefit the most from protective cave environments and show in higher proportions there, whereas more durable proxies would subsist in both site types at levels closer to the original deposition quantities. Whilst this is the case for burnt lithics, the lack of burnt bone, an equally durable proxy, in open-air sites is confusing. Two competing theories attempt to explain this; one is that fire use was similar in both site types, and taphonomic issues affected open-air sites far more, with the relative absence of burnt bone in the latter being explained by preferential cooking in caves. The other theory is that there was originally much more fire in caves than open-air sites; the abundance of burnt lithics in the latter is explained by preferential lithic heat-treatment outdoors, leaving more burnt lithics there. Further testing the intentionality of burnt lithics at many more sites could help solve this issue. If they were intentional (especially if one site type had intentionally-burnt lithics and the other had accidentally-burnt ones), then the latter hypothesis stands; if generally unintentional, the former is suggested.

Finally, spatial distributions of Neanderthal fire proxies appears generally uncorrelated with latitude. This suggests that ease of gathering or firestarting ability did not greatly hinder northern European Neanderthals from using this technology frequently; and proposed fuelwood abundances in southern regions did not lead to greater amounts of fire use. The exception to this is apparent groupings of burnt lithics in certain neighbouring Iberian sites – this can be explained either culturally (intentionally or unintentionally), or geologically if it relates to similar groupings of underlying substrates. There is however some correlation with altitude, suggesting an inability of high-altitude Neanderthals to collect sufficient fuelwood. Given that Neanderthals were highly mobile however, and presumably across many altitudes, this does not preclude a single group from using fire in their lowland sites, even if they could not in their highland ones.

Having reviewed the general *presence* of Neanderthal fire, I can conclude that it was a common Neanderthal technology, and therefore its further pyrotechnic-dependent technologies can be studied in greater depth, and which are recognisable in the Middle Palaeolithic record. Given the plethora of site types seen here, between the 45 completely fireless ones and the 25 with every proxy present, fire usage may have been highly varied, some groups merely using fire as a one-off, and others using it daily and fully understanding its transformative properties. These considerations and questions form the topic of the next chapter.

Chapter Four: Neanderthal Fire Technologies.

We have seen in Chapter Three that Neanderthal fire is a common phenomenon. I have demonstrated that most sites retain some trace of fire, which unlike earlier hominin sites, are unlikely to have been natural wildfire. Fire proxies have survived even where discrete hearths have not, and microscopic studies often drastically increases chances of finding fire in otherwise "fireless" strata. I can conclude that Neanderthals, as a species, used fire frequently, across many sites. Neanderthal individuals or groups may have seasonally lived in fireless and fire-using sites. Even groups not using fire in all their home bases probably encountered pyrotechnology at some point in their lives.

I: Aspects of Fire Use.

The second big question about Neanderthal fire use, alongside its prevalence, is its degree of complexity. Advanced fire, as used by present-day *H. sapiens,* is characterised by five main features distinguishing it from natural, uncontrolled fire.

1) We light fires ourselves. Neanderthals may have created fire, according to Sorensen et al. (2018), or borrowed it from naturally occurring wildfires, according to Sandgathe and Dibble (Dibble et al. 2017, Sandgathe et al. 2011). Correlations between fire frequency and climatic cycles in certain sites suggests that some Neanderthals (e.g. Pech de l'Aze and Roc de Marsal - Sandgathe et al. 2011) could not light fires. However, my data suggests that fire is very widespread in the Middle Palaeolithic, occurring in some very cold sites, and thus at least some groups probably mastered firelighting, possibly utilising pyrite and Mousterian bifaces as strikelights (Sorensen et al. 2018).
2) We perform fire-dependent activities. Everyone near hearths benefits from light and heat, which extends the working day, allowing activities including tool creation/maintenance, feeding, grooming, socialising etc. However, these activities are not exclusive to hearths as a) some could be done in darkness without fire (feeding, socialising etc.), and b) even light-dependent activities could be done at other times of day. Activities *requiring* fire are transformative technologies, utilising fire's nature to change one substance into another more useful version of itself. Some transformations improve object quality (organic or non-organic toolmaking), and some food quality (cooking). Both sets of activities are carried out by modern and archaic *H. sapiens*

(Dunbar and Gowlett 2014). *H. neanderthalensis* may also have used fire-integral transformative technologies, but how common this was is debatable. This chapter debates issues relating to Neanderthal tool manufacture and cooking.

3) We optimise fire by hearth construction, including ringing with stones to delineate flames, sinking in pits or creating barriers to reduce windchill (e.g. Buzea et al. 2008), and erecting flues to carry off smoke. Neanderthals sometimes lit fires on bare ground without no preparation aside from removing some vegetation (Leierer et al. 2019). The exceptions from this rule, already noted at Kebara (Meigen et al. 2007), are notable precisely because they are uncommon. Admittedly, caves are more environmentally stable than open-air sites, with gusts less likely to extinguish more exposed fires; however they are more enclosed and smokier. Many open-air Neanderthal sites are also without prepared fireplaces, and several cave sites had hearths in more exposed entranceways (e.g. Grotta di Fumane, Gruta Nova da Columbeira – Romandini et al. 2014, Zilhao et al. 2011). This may have been to signal their presence to other groups, remove smokiness, or to deter predators. Nonetheless, generally Neanderthals did not practice these behaviours, and any examples of hearth preparation are more likely to be individual innovations, quickly dying out rather than becoming group traditions.
4) We optimise fires by the fuels used. Certain fuels are objectively better than others, with higher calorific values and lower ignition temperatures (Ragland et al. 1991). Other fuels serve specific functions; wet branches with leaves attached are used by Evenki people for smoking hides (Albert et al. 2003, Henry and Thery-Parisot 2014). Finally, certain fuels are preferred due to subjective individual or group traditions, or selected against for ritualistic taboos. Modern Yoruba people reject *Akoko* and *Iroko* fuelwood from positive associations (*Akoko* wood is used for throning ceremonies) or negative ones (*Iroko* is believed to harm children's health - Akintan et al. 2018). However, these preferences depend on *H. sapiens'* abstract thought and ritual understanding, which may be different in Neanderthals. Hominins familiar with fire may optimise its fuel; those unfamiliar, or newly-familiarised, might burn whatever was most available. Nonetheless, certain modern hunter-gatherer groups, undoubtedly proficient with fire, burn genera indiscriminately. North-coast Alaskan people burn any driftwood (Alix 1998), and indiscriminate fuel use is seen archaeologically from the Middle Palaeolithic until today (see Table 5.1, p.134 for details). Whether Neanderthals were likewise indiscriminate, or selected for specific fuel properties, is currently poorly understood. If Neanderthals selected fuel according to any criteria of quality, then as

well as indicating thoughts of improving their fires, this also indicates past fire experience. If unselective, or selected according to arbitrary characteristics, they may be inexperienced with fire, or simply unselective like the Alaskan people. Chapter Five explores "good" fuels, choice, and Neanderthal selectivity.

5) We extinguish fires that has served their function, through disassembly, watering, covering with earth, or blowing it out. This prevents potential fire spread to other areas, conserves fuel resources, and avoids unwanted attention. Again, modern hunter-gatherers do not always do this. Since extinguishing only creates ephemeral traces, there is only one recorded instance of Neanderthals deliberately extinguished a fire by piling earth onto it, in Shanidar Cave (Smirnov 1989, p.216). As charcoal is increasingly produced in reducing environments, suddenly-smothered fires might increase proportions of charcoal to ash. However many other factors cause reduction, and certain extinguishing actions like disassembling and blowing do not cause reducing environments. Thus this act is impossible to determine archaeologically.

Two elements of advanced Neanderthal fire use are potentially present but under-investigated in Middle Palaeolithic contexts; pyrotechnic-dependent technologies, and fuels burned. The former may depend on the latter if particular technologies require particular fuels. Three fire-dependent technologies which Neanderthals might have undertaken are lithic heat-treatment, making hafting adhesives, and cooking. Other manufacture-related technologies undertaken, such as skin-drying/tanning, leave no archaeological signatures. This chapter addresses these advanced technologies regarding the utility and complexity of fire for Neanderthals. In discussing heat-treatment, I conclude that Neanderthals not heat-treating lithics does not imply an inability to master it. Rather, heat-treatment was disadvantageous for them, given its increased time and fuel costs. Neanderthal adhesive heat-preparation for lithic hafting is better-evidenced and proves that Neanderthals certainly had the capabilities for complex, planned tasks. I find that Neanderthals cooked in many regions, despite much evidence of this technology being ephemeral and unrecognised. Many hearths therefore would be optimised for cooking, or for archaeologically-invisible tasks (light and heat for miscellaneous tasks nearby). I conclude that whilst some Neanderthals undoubtedly used advanced pyrotechnic-dependent technologies, their ephemeral natures precludes them from being prime indicators of Neanderthal technological advancement. I suggest that fuel selection is the best way to study this, and Chapter Five addresses this, and the question of choice and selectivity.

II: Heat-Treatment.

Lithic heat-treatment is a common modern hunter-gatherer practice to improve lithic knapping properties. It is first seen with *H. sapiens* at Pinnacle Point in South Africa at 164ka BP (Brown et al. 2009, Mourre et al. 2010), at Porc Epic in Ethiopia at 70ka (Clark and Harris 1985), on European Solutrean laurel-leaf points (Aubry et al. 2003), and in Asia by 32-11ka BP (Zhou et al. 2014). Whilst becaming mostly obsolete in the Early Bronze Age for metal-users (Domanski and Webb 2007), today non-metal-using people in North America, Australia and Africa commonly practice lithic heat-treatment on cherts, chalcedonies, quartzites and obsidian (Collins and Fenwick 1974, Schmidt 2016). Although heat-treating processes vary, temperatures required are generally c.200-500°C, depending on the material (Ahler 1983, Hurst et al. 2015, Luedke 1992, Schmidt and Morala 2018). Coarser-grained quartzes must be heated more than cherts to structurally alter (Schmidt et al. 2013, Sollberger and Hester 1973, p.182, Speer 2010). The rate of change of temperature is crucial. Overly-rapid heating or cooling causes thermal shock and fissuring (Mercierca and Hiscock 2008), ruining finer-grained cherts, although heat-fractured silcrete is still knappable (Schmidt 2016). Patterson (1995) recommends temperature changes of under 1.25°C/min for chert; silcretes can withstand changes of up to 20°C/min (Schmidt 2016). This rate of change is particularly important for larger lithics, as they thermally fracture more easily than smaller specimens (Schmidt et al. 2013). To heat slowly, lithics are rarely exposed to flames themselves, instead being thermally insulated in sand baths beneath hearths (Ahler 1983), or between layers of sawdust covered in burning charcoal (Laveri 1962). The Kidja Australian Aborigines bury lithics under smouldering firepits, covered with coals and hot sand for 48 hours (Akerman et al. 2002). Heating durations required for changes to take effect ranges between 50 minutes (Fukada and Nakashima 2008) and 2.5 hours (Schmidt et al. 2012). However, the whole process, including slow heating and cooling, takes 10-48 hours (Hurst et al. 2015, Olausson and Larsson 1982), and sometimes up to 4 days (Laveri 1962).

Heating lithics causes them to become more homogenous; intergranular pore spaces decrease as silica is recrystallised, making variably-sized crystals more equigranular (Gryba 2002). This is described by the Ostwald ripening dissolution-reprecipitation process, whereby many smaller poorly-ordered crystals grow into fewer, larger, better-ordered ones (Parks 1990, Sander 2009). Flaws and impurities are ‘healed’ by matrix impurities acting as a flux, welding the whole structure together (Graetsch et al. 1985, Monik et al. 2021). This causes more homogeneous, regular fracture behaviour when knapped. Cracks no longer propagate around particles and along flaws, but rather along more predictable lines based on knapping angles (DeForest and Lyman 2022, Nadel 1989), more like glass or obsidian (Frahm and Feinberg 2013, Purdy 1974, p.51). Water loss slows crack propagation, causing smoother fracture planes. Strong silicon-oxygen bonds are replaced with much weaker hydrogen bonds, causing innately weaker structures (Bachellerie et al. 2019, Blacic and Christie 1984). The Vickers indentation hardness (determining object hardness by measuring the loading capacity on a given surface area of a material) decreases with heating to c.200-400°C, but increases at higher temperatures (Domanski and Webb 2007, Speer 2010). Water movement and silica crystal microfracture decreases the rock's strength (Flenniken and Garrison 1975, Milot et al. 2017) and reducing the force required in manufacturing processes (Johnson 1979, Nickel and Schmidt 2022).

Consequently, regular and heat-treated lithics display very different knapping characteristics. Heat-treated lithics are better for learning or teaching knapping on; knapping fractures propagate more predictably, product standardisation is increased (Maloney and Street 2020, Wilke 1996), and fewer imperfect lithics are rejected due to undesirable step/hinge fractures (Holyoke et al. 2020, Rick 1978). Longer, more useful blades can be produced from heat-treated lithics (Byers et al. 2014, Flenniken and Garrison 1975). Tougher, lower- quality local rocks can be effectively worked by increasing their quality through heat-treatment (Brown et al. 2009, Hurst et al. 2015, Patterson 1979). Increasing proportions of workable stones would be especially useful in periglacial Middle Palaeolithic landscapes, where repeated freeze-thaw cycles reduced surface lithic quality by microfracture, as well as deep snow and frozen ground causing seasonal shortages (French 2013, Rasic 2004, Rolland and Dibble 1990). Although lithics heat-damage is undesirable, negative bulb scars of pot-lid flakes provide good angular facets for striking platforms (Domanski and Webb 2007). If properly cooled, a stone's mechanical properties may be improved, as compressive strength increases (Key et al. 2021, Purdy and Brooks 1971, Key et al. 2021), albeit at the expense of tensile strength (Bustos-Perez and Preysler 2016, Sollberger and Hester 1973, Bustos-Perez and Preysler 2016). Finally, the finished pieces are rubified, and glossier due to flatter planar fractures – this may imbue the object with special meanings, increasing its value for the individual, or within intra- or inter-group trades (Domanski and Webb 2007). Local heated materials can imitate other, exotic ones (Nadel 1989, Yegorov et al. 2020). The points created are sharper than non-heat-treated ones, properly displaying superior skillsets of experienced knappers (Hanckel 1985, Mraz et al. 2019). Heat-treated lithics would have been ideal for sharp cutting implements, such as razors.

Given heat-treatment’s utility and that many *H. sapiens* groups used fire for this purpose, did Neanderthals do likewise, and if not, why not? In order to determine deliberate heat treatment, tools must have been demonstrably heated pre-knapping into shape, and they must not evidence heat-fracture or other negative effects indicating uncontrolled heating. Thus, common evidences for heated lithics including fissuring, potlidding etc. cannot be used here. As outlined in Chapter Two, other suitable evidences could include rubefaction/surface darkening (though this could have been lost through subsequent reduction), lustre of exposed faces and ESR signal intensity. In order to prove deliberately pre-knapping heating, refittable waste flakes should also show similar indications of past heating; however it is rare that tools are found in the site where they were created. A more reliable indication might be refitting waste flakes from different areas of the site, displaying similar heating effects, suggesting heating and subsequent knapping and scattering.

II.I: Neanderthal Heat-Treatment: Methodology.

Although burnt lithics are found in 91 Middle Palaeolithic sites (Chapter Three, p.67), most are unintentionally heated. To search for evidence of intentional heat-treating, I initiated a search using the Birkbeck library and online resources. The research used online repositories, and search engines including Google Scholar, Research-Gate and Elsevier search, using keywords in English, French, Spanish, German and Italian for heat-treatment, thermal alternation, potlidding, controlled heating etc. It was important that the heat-treatment was considered deliberate by at least one publication, and preferably more. Examples where burnt lithics were found but no authors suggested their intentionality were rejected, as I did not research the lithics directly and am in no position to comment on their intentionality.

II.II: Results.

Deliberate Neanderthal heat-treatment is only convincingly evidenced at five sites; Ras El-Kelb, (Copeland 1998), Les Forets (Duttine et al. 2005), Mediona I (Clemente 1995), Brugas (Meignen 1981) and Sesselfelsgrotte (Agam et al. 2023). Whilst compelling enough to indicate that Neanderthals, as a species, could undertake this technology, it generally suggests that they mostly did not, or that if they did, the evidence is lost.

This may in part be due to archaeologists not noticing heated lithics, and if finding them, attributing them to natural causes. Lithic heating, if not cracking rubifying lithics, is often overlooked. For lithic heat-treatment, and indeed any advanced pyrotechnic technology traditionally considered exclusive to our species (such as birch-bark pitch manufacture until recent discoveries – see Schmidt et al. 2023 for the most recent discussion on the debate), this issue has similar methodological problems to debates about Neanderthal burial and fire use. Evidence may not be found because it is not looked for, and if found, is unexpected and ascribed to natural causes. Indeed, a lithic perfectly heat-treated and subsequently knapped does not prove intentionality; the lithic could accidentally have been ideally placed in an optimum environment – and these five Neanderthal examples could be no more than chance. However, given the aforementioned difficulties of thermal shock from overly-rapid heating and cooling, and the fact that lithics often have to be buried underneath fires in order to achieve this effect, it is unlikely that Neanderthals would excavate beneath their fires and come across these lithics. It is far more likely that these examples are in fact deliberate.

Nonetheless, lithic heat-treatment was infrequently used by Neanderthals, and would not have been generally considered when planning hearth events. Why did they lack lithic heat-treatment, a complex forward-planning technology analogous to fire use itself? If heat-treatment was a distinct benefit which they did not use, this calls into question their technological advancement, as well as their mental proficiency as a whole. If however, heat-treatment represents behavioural shifts rather than obvious optimisation, providing problems as well as improvements, then their lacking this technology could be seen as either an active rejection, or that this technology never developed due a lack of selective pressure. Many modern human hunter-gatherer groups do not heat-treat lithics, yet we do not question their behavioural modernity.

The reasons why Neanderthals *might* not use this technology at first appear clear. Although heat-treatment can make knapping easier, this knapping requires different skillsets to normal knapping, and depends on so many variables including fatigue level, unquantifiable practice, and split-second judgements about force placements (Bleed and Meier 1980). Heat-treatment itself requires intense skill and judgement; stones should be heated, but not so as to cause harmful potlids, fissures or cracking, which actively *decrease* raw material quality. Whilst knapping is a very visual task, and can be accurately learnt by observation from first principles, heat-treatment beneath hearths is hidden and over longer periods, requiring explanations of the transformation and its timings. Young Neanderthals might not understand how lithics, hidden from sight, became heat-treated (but not much altered visually) and heat-damaged if heated too rapidly. If Neanderthals lacked complex language, this may have limited complex teaching. The difference between this technology and cooking, both requiring precise timing, is that cooking (unless in subterranean pits) is always visible – meat visually transforms slowly from raw to cooked, and potentially burnt. Furthermore, the finished cooked product (meat or vegetables) is visually and olfactorily different from its raw counterparts, whereas heat-treated stones resemble unheated ones. Cooking could be transmitted by visual learning rather than explanation. Thus this technical, hidden technology may have been too complex if Neanderthals were cognitively-inferior to our own species.

The benefits of heat-treatment outlined above are varied and many. In particular, greater flake-per-core ratios of heat-treated lithics would have especially benefitted Neanderthals suffering from lithic shortages in glacial winters. Neanderthals sometimes used low-quality local lithics (e.g. Frouin et al. 2014, Marquez et al. 2013), and heating them could avoid substitution with innately higher-quality, more distant ones. Given these benefits, its absence must either suggest minimal fire and/or in-depth planning activities, or that lithic heat-treatment would not have benefitted them. Heat-treatment effectiveness varies depending on the rock sources used; recrystallisation processes depend on silica content, and the effects are more pronounced in very fine-grained microcrystalline cherts (Banfield and Zhange 2001, p.13). 'Repairing' internal flaws in the rocks through heating depends on the presence of chalcedonic matrices, and is less effective in cherts, jaspers and silcretes (Graetsch et al. 1985). Thus some stones are worth heat-treating, and others not (Byers et al. 2014). The effect also depends on more immediate, fluctuating variables including water content, which increases in lithics foraged from riverbeds. The lower quality of Neanderthal raw lithics may have made heat-treatment uneconomical. Many comparable Middle Stone Age heat-treatments, such as those in Diepkloof, occurred on silcrete rather than the cherts characterising the European Middle Palaeolithic. Treating silcrete is much easier, as it does not require dedicated heating environments such as sand baths, but could have been done within fires alongside other activities such as cooking, with only minor supplementary time and firewood investments (Schmidt et al. 2013, Stolarcyzk and Schmidt 2018). Occasional Neanderthal heat-treatment of chert would therefore represent a novel technology, disconnected from and more technically demanding than MSA heat-treatment. MSA heat-treatments also occurred in warm African climates; in cold environments, the fire's heat dissipates too rapidly in frozen ground to heat buried lithics properly (Mandeville and Flenniken 1973). In both instances, Neanderthals would have suffered more difficult conditions for heat-treating, and so cannot be directly compared with MSA *H. sapiens* in this instance.

Heating lithics is costly, requiring c.8kg of fuel for treating four cores (Brown et al. 2009, Wadley and Prinsloo 2014); these costs increase if steppic Middle Palaeolithic landscapes afforded little fuel, given the long times needed for heat-treatment (Brown and Marean 2010, Eriksen 1997). Furthermore, effective heat-treatment requires burying lithics beneath hearths, extinguishing the fire and subsequently excavating and recovering the cores. If Neanderthals could not easily create fire, relying instead on keeping fires alight, then extinguishing and relighting, or transferring flames to alternative hearth spots during this process, would have been too risky. They could have mitigated this, however, by wrapping lithics in clay and baking them in ongoing fires (Reynolds, pers. comms.).

Thus far, this technology would be advantageous but too costly for Neanderthals as opposed to contemporary African AMH. However, heat-treated lithics have several *innate* disadvantages compared to their normal counterparts. Tensile strength is decreased, causing increased platform collapse and crescentic snap fractures during knapping (Amrick 2022, Hayden 1979, p.134), and more lateral snaps and reverse fractures during use (Johnson 1979). Use-lives are shorter due to quicker wear of sharper, thinner edges (Domanski and Webb 2007, Monik et al. 2021, Olausson 1983). Heat-treatment may actively worsen tools requiring strength and durability and the expense of sharpness (drills, scrapers, adzes etc.). Neanderthals used fewer projectiles or microlithic technology, save for some micro-Mousterian Mediterranean points, relying instead on handaxes and discoid scrapers, tools requiring longer use-lives. Heat-treatment may have actively harmed these tools (Ibid, Ahler 1983). Whilst the *H. sapiens* toolkit may have been advantageous over Neanderthal technology for European subsistence, and heat-treatment may have provided that competitive edge (Webb and Domanski 2009), nonetheless for typical Neanderthal toolkits, heat-treatment may not have been beneficial. In summary, the lack of Neanderthal heat-treatment comes down to three models.

- One hypothesis is that, unlike *Homo sapiens,* Neanderthals simply could not use this technology. Either they lacked pyrotechnic experience, or lacked language and communication skills to communicate this complex visually-hidden technology to others. Here, Neanderthals could create fires and use them for some purposes but not others.
- The second position is a middle ground; Neanderthals did not heat-treat lithics not because of incompetence, but because of environmental constraints. African silcrete heat-treatment would have been far easier than chert heat-treatment in colder conditions. If Neanderthals did heat-treat, it would show more advanced technologies than used by contemporary *H. sapiens.*
- A final model is that Neanderthals could in theory heat-treated their lithics, but them not doing so represents either active avoidance, or a lack of selection towards this process. Neanderthal tools types would have made heat-treatment superfluous, as normal lithics would be better for their functions than heat-treated lithics, which would also have used up valuable time and fuel. In this instance, occasional Neanderthal heat-treatment may be individuals attempting this technology, or groups using different lithics and toolsets for which heat-treatment would have been beneficial (of which we have no evidence). This technology did not provide sufficient evolutionary or cultural advantages to promote its use. Only with the later *H. sapiens'* projectile toolkits did it became valuable, in Upper Palaeolithic Aurignacian, Solutrean and Gravettian sites (for site lists, see Domanski and Webb 2007, p.164).

III: Hafting Adhesive Preparation.

A subsidiary technology associated with lithic knapping is melting and creating hafting adhesives for composite technologies (binding lithics to organic handles). This represents a halfway technology between heat-treatment and food preparation, as the substance is treated more like food than any other tool-associated technology. Birch-bark is not edible, and yet is a rare example of organic materials being fire-altered (aside from occasionally fire-hardening wood). It is associated with inorganic lithics and tool creation, but is frequently made with organic birch-bark, part of the fuel-food object category, although sometimes with natural bitumen (Boeda et al. 2008a). Thus, it used organic resources as tool components. It very visually changes solids into liquids (and back into solids once cooled), similar to visually cooking food, but neither the raw nor liquid state is edible, and thus not associated with imminent hunger and survival. Its transformation is associated with future planning and tool maintenance rather than satisfying immediate needs, and the process is much more visible than lithic heat-treatment. It is a pyrotechnic-dependent technology, although working under more fire conditions than lithic heat-treatment (see Kozowyk et al. 2017, 2023 for details).

Hafting material residues remain on finished tools, although we lack the organic handles to which they would have been attached. Birch-bark tar residues survive at Campitello (Mazza et al. 2006), Bockstein (Conard et al. 2012, p.237), Inden Altdorf and Konigsaue (Koller et al. 2001, Pawlik and Thissen 2011) – bitumen residues at Fossellone and Sant’Agostino (Degano et al. 2019), Sesselfels-Grotte (Rots 2009), Biache-Saint-Vaast (Rots 2013), Umm el Tlel (Boeda et al. 2008a,b), Gura Cheii-Rasnov (Carciumaru et al. 2012) and Hummal (Hauck 2010). Residue-coated lithics sometimes represent a large proportion of the sample, including 200 of 1,000 lithics at Umm el Tlel (Boeda et al. 2008a). Bitumen may have been melted on fires, or applied directly; birch-bark however must be melted. Hafting can also be inferred from wear patterns on lithics (Boeda et al. 1999), although of course some hafting methods may be fireless. This common hafting practice by Neanderthals suggests that this technology was relatively common amongst them, with fire playing a non-exclusive role in this. Plant-based tars are distilled at 200-500°C (Fagernas et al. 2012, Nilsson et al. 1999, Pakdel et al. 2002, Puchinger et al. 2007), and manufactured in ceramic containers by modern hunter-gatherers (Kozowyk et al. 2017); however pre-pottery societies have several alternative methods. The simplest, ‘ash mounds’, places hot ashes and embers over tightly-rolled and tied birch bark; over time, tar precipitates onto the bark and is collected. This method could easily have been practiced by Neanderthals who cleaned hearths after use, and had cordage technology to tie rolls with. This method would follow on from observations of tar naturally precipitating from birch bark, a common Palaeolithic fuel (Urban and Bigga 2015). This method however gives poor yields of 1g of tar for every 100g of bark used (Kozowyk et al. 2017). The pit method involves birch bark placed on an organic mesh, covered in earth, and a fire lit on the mound. Whilst offering much higher yields of 9.6g tar per 100g bark used (Ibid), this method is much more complex. It is a non-visible transformation of material in a fire, more similar to heat-treating lithics than cooking, and would require re-lighting a fire after the burial, and extinguishing it after the tar had precipitated, a potentially difficult action if Neanderthals could not create fire at will. There are no known instances of Neanderthal fires on raised mounds for this purpose. With no evidence for how the adhesive was melted, we may assume the simpler 'ash method' (Kozowyk et al. 2022).

The evidence here suggests that Neanderthals used fire for organic transformations related to tool manufacture. Earlier Lower Palaeolithic evidence of Clactonian fire-hardened wooden spear tips (Ennos and Chan 2016) evidences similar technologies in species ancestral to Neanderthals, with fire visibly transforming organic materials into better tool components. A single similar Neanderthal instance, of fire-hardened digging tools, has been found at Poggetti Vecchi, Italy (Aranguren et al. 2018). Neanderthals apparently mentally associated organic materials with fire, but not so easily inorganic lithics; they could perform pyrotechnic-dependent technologies relying on observable visual changes, but not so easily ones with hidden transformations.

IV: Neanderthal Cooking.

In cooking, organic materials are visually transformed. On this principle, Neanderthals should have been able to cook. I have already discussed how *H. sapiens* are obligate fire-users primarily because of needing cooked food. Despite their protein-rich high-energy diets, Neanderthals' high energetic needs (Churchill 2006) meant that fire would have been especially valuable for cooking. Did *H. neanderthalensis* represents a species who absolutely *required* fire for this purpose? Fireless levels in Pech de l'Aze and Roc de Marsal (see Chapter Two), and fireless sites in my survey (Chapter Three) must represent fireless Neanderthals who nonetheless could survive, and eat. These groups may have been unfit however, or even represent groups dying out, as a result of this lack of fire.

Cooking would have increased individual or group fitness, as well as individual desirability to potential mates and subsequent reproductive success. Neanderthals may not have suffered from not cooking during stable climatic intervals, but during unstable climatic periods that caused Neanderthal extinction from 44ka BP (Melchionna et al. 2018), cooking gave *H. sapiens* the competitive edge. This may have occurred either by direct competitive exclusion of Neanderthals (Goldfield et al. 2018), or as a more passive process if Neanderthals and humans were not competing for identical food types in the same areas. Whether we actually find cooked food in the Neanderthal record is therefore important for this hypothesis – if Neanderthals did cook, then other advantages such as clothing (Gilligan 2007) must have given modern humans advantages in these periods.

Cooking, or rather, food preparation in general, is an important mechanism throughout evolutionary history which has both driven and resulted from many evolutionary changes. I say food preparation in general, as actual cooking (exposing food to heat) only represents a small portion of this process. Other parts include defleshing, filleting, washing, separating into edible and inedible (or optimal and suboptimal) parts, which improve flavours and/or qualities of foodstuffs. Animals sometimes prepare food in this manner; macaque monkeys flavour sweet potatoes with saltwater (Matsuzawa 2015, Nishida 1987), and gorillas create 'leaf parcels' to shield their mouths from harmful parts of meals (Byrne et al. 2011). Such practices may have occurred in fireless as well as fire-using societies, but are archaeologically-invisible. Today, non-human animals do not cook, as they do not use or control fire. However, studies have shown that the capability is present. Warneken and Rosati (2015) found that chimpanzees exchange raw potatoes for cooked ones, demonstrating an awareness of cooked food and its benefits. But the animals may not have understood cooking processes, as the potato cannot be observed cooking, and this transfer may just represent flavour preferences rather than representing any survival benefit (Beran et al. 2017). This may be due to the Maillard reaction, whereby cooked meat smells are chemically similar to volatile compounds present in preferred raw plant foods (Carmody and Wrangham 2009a). Animals completely unacquainted with fire, including rats and cats, often prefer cooked to raw foods (Wobber et al. 2008), highlighting that preferences for cooked diets is uncorrelated with fire use. Nonetheless, chimpanzees, although not utilising fire, are not unduly afraid of it unlike some animals (Gowlett 2016). Early *Australopithecines* might have encountered pre-cooked carrion and tubers as they followed wildfires around the landscape, developing preferences for cooked food. It was no great leap to associate cooked food with fire. The greater leap would have been actively cooking it oneself, either on controlled or uncontrolled fires; once achieved, cooking is an obvious, visual process that can be learnt without direct teaching or complex language.

Cooking provides many immediate benefits. It breaks down tougher foods into easily-chewable masses. This is particularly important for weaning children and elderly individuals with weak teeth or masticatory muscles. This preservation of the elderly is important for the "grandmother hypothesis" (Alvarez 2000) whereby older community members teach children important cultural and survival knowledge, and give fit adult individuals more time for foraging. Neanderthals generally died in their 20s and 30s, but some individuals survived much longer, often with severely debilitating injuries. St Cesaire 1 survived severe head trauma and Shanidar 1 was half-blinded, with a withered right arm and partial paralysis, and could have lived as long as 50 (Spikins et al. 2018). Elderly Neanderthals frequently lost their teeth (e.g. Bau de l'Aubesier 11 – Lebel et al. 2001) and could not have chewed tough food; softened cooked food could have been part of specialist care shown to them. Breaking down food is also important for dealing with tougher fallback foods in harsh seasons (Wrangham et al. 1999). Cooked, easily-chewable food can also be eaten on average 10-20% quicker than their raw counterparts (Wrangham 2017), saving time when eating which could be used more valuably in other activities. If eating is undertaken in open landscapes, this may represent moments of risk from predators, that cooking helps to mitigate. However, these masticatory benefits could instead have been conferred by blending or crushing foodstuffs, without cooking. Thus although cooking provides such benefits, other (fireless) processes may also have done likewise, albeit with higher preparation costs.

Cooking however also breaks down microscopic food molecules into smaller ones; for instance, transforming starch into dextrin and maltose (Wandsnider 1997). This is impossible through fireless preparation methods (Groopman et al. 2015). Molecules which cannot be metabolised when raw, such as cellulose, can then be properly digested (Attwell et al. 2015). Other molecules which can be digested at high metabolic costs, use less energy when cooked (e.g. proteins denature by heat into component amino acids – Wandsnider 1997). As a result, although no energy is *added* to food by cooking, nonetheless reduced digestion costs mean that energetic contents of cooked food increase by c.10% for meat and by c.30% for vegetables (Carmody and Wrangham 2009a, Carmody et al. 2011).

Cooking also kills bacteria and other food pathogens. As well as pathogens potentially causing fatal diseases, even coping with milder infections through fevers increases human energy expenditure by 7-13% (Carmody and Wrangham 2009a, 2011). Animals with routinely better health expend less energy than unhealthy ones, and cooking prevents food-borne disease. Cooking also kills spoilage bacteria, meaning that cooked food lasts longer than its raw counterparts (Wandsnider 1997) and facilitating storage. Certain foods, particularly plants, have naturally toxic compounds to defend against being eaten. For instance, lectin proteins in legumes agglutinate red blood cells (Jaffe 1980, p.77, Mrazkova et al. 2019). However, cooking denatures and nullifies many toxins (Cutts 2021, Stahl 1984). This not only allows dietary inclusion of previously toxic food, but also reduces evolutionary requirements to discriminate between toxic and nontoxic food, if much is rendered safe through cooking (see next paragraph for contrary arguments). This saves time, both in learning and day-to-day foraging.

Alongside these benefits, this technology comes with costs. As with any technology, care is required or foods will burn, either becoming completely inedible or losing energy to carbonization processes (Henry 2017). Over-cooked food poses carcinogenic risks (Ibid), though this may have posed minimal practical disadvantage given short Neanderthal lifespans. Certain meat cooking techniques cause inevitable loss through fat-dripping (Attwell et al. 2015), though this lost energy may be partially reclaimed if it fuels the fire. Heat usually denatures toxic compounds, but some compounds withstand heat, and heat enhances others (Wandsnider 1997). These compounds pose risks, especially in fire-using societies which cannot discriminate against toxic plants. Heat-destruction of bacteria, although generally beneficial, may reduce gut microbe diversity, causing associated health problems (Henry 2017). Finally, the process of cooking may itself be a disadvantage. Despite the time saved in eating and food-processing behaviours, cooking itself takes time and uses the hearth, preventing other open-fire technologies like hafting adhesive preparation. Those cooking by hearths risk burns and long-term health risks from smoke inhalation (Ibid). Since cooking involves delayed-gratification, it increases risks of freeloaders compared with immediate consumption (Twomey 2013). The delay in accumulating food, bringing it to processing areas, and processing and cooking it, increases risks of theft by other group members. Furthermore, the closer food is to being cooked, the more valuable it becomes due to its improved nutritional properties and the less future investment is needed in it, hence the more likely it is to be stolen (Wrangham et al. 1999). The fact that cooking *was* adopted however by all *H. sapiens* indicates that these concerns are outweighed by the benefits, at least for our own species. It remains to be seen whether this cost-benefit ratio also applied to *H. neanderthalensis* cooking.

Over perhaps millions of years, cooking has imparted important evolutionary effects to those practicing it. Cooking makes foraging and acquiring food easier, as assessing levels of pathogens/innate toxicity is unimportant if both are annulled by fire. Chimpanzees can inspect carcasses for pathogens (Muller et al. 1995), and by proxy it is believed that early hominins could also do so (Smith et al. 2015). However, with fire, these traits can be lost without major detriment, allowing other behaviours to emerge. Cooking also has important societal implications. Time necessarily spent around hearths promotes sociality and group bonding (Gowlett and Wrangham 2013) – modern human attention peaks at 6-7pm in the evening, a time for cooking (Schmidt et al. 2007). Sub-group coalitions may have formed to prevent freeloaders and food theft; smaller females may have formed protective relationships with male co-defenders for this purpose by extending their period of sexual attractiveness (Wrangham et al. 1999). This would in turn increase the numbers of matings per pregnancy, reducing male-male competition, and thus the selection for extreme sexual dimorphism (Ibid). This trend exists in the archaeological record since *H. erectus*; by the Middle Palaeolithic, Neanderthal sexual dimorphism was similar to modern-day humans (Trinkaus 1980). If cooking and its increased costs of delayed-eating drove these changes, then cooking could have emerged alongside the *Homo* lineage.

Extracting more energy from cooked food also has important implications for the previously-mentioned Expensive Tissue Hypothesis. Neanderthals traditionally committed to high-quality, high-protein diets based on large ungulates (Goldfield et al. 2018), and this narrow-spectrum diet may have contributed to their extinction. Once their preferred megafaunal diet died out due to climate shifts, Neanderthals were unable to effectively forage and died out (Timmermann 2020). Neanderthals were top-level carnivores, as seen through molar microwear patterns (Krueger et al. 2017, Lalueza and Perez-Perez 1993), dietary isotopes (Bocherens et al. 2005, Richards and Trinkaus 2009) and butchered faunal remains (e.g. Smith 2015). However, there is more evidence than was once thought for broad-spectrum Neanderthal diets, of underground tubers (Hardy 2010), fibrous plants and bulbs (Hardy et al. 2012), moss and fungi (Weyrich et al. 2017) and marine resources (Hardy and Moncel 2011). The latter are particularly common, noted in ten caves from Spain to Russia (Adan et al. 2009, Bicho and Haws 2008, Derevianko et al. 2005, Fiore et al. 2004, Patou-Mathis 2004, Rigaud et al. 1995, Stringer et al. 2008). Neanderthals had apparently already adapted to broad diets through choice or environmental necessity, certain plant types of which were lower-quality. Large Neanderthal brains are unlikely to have been sustained on raw diets that weren’t focused on large ungulates alone. To sustain this, supplementary cooking may have been required.

IV.I: Behavioural Change versus Evolutionary Stability.

Behaviours may of course emerge on timescales on which evolutionary features cannot be traced. Neanderthals increasingly broadening their diet over 50,000 years (many dietary innovations are seen only in the latest Neanderthals) would be archaeologically-apparent but morphologically-invisible, as Neanderthals still carried ancestral traits for eating raw food. Gilligan (2007) argues that Neanderthal reliance on genetic adaptations towards cold living delayed cultural adaptations towards clothing and related technologies. Thus *H. sapiens,* who instead coped through behavioural alterations, could better withstand change than Neanderthals. Similar theories can be posited for cooking; given pre-existing Neanderthal adaptations towards eating raw food (large teeth, strong biting power etc.), they would not need to alter this with cooking behaviours. However, this theory would hold true for larger-teethed archaic *H. sapiens*, who did not *need* cooking for survival. Their adoption of cooking suggests cultural change subsequently caused evolutionary change, which in turn rendered cooking essential. Neanderthals could also have altered their behaviours, although not obliged to do so. Had they survived longer, evolutionary changes may have followed and they may also have become obligate cookers. Comparing *H. sapiens* and *H. neanderthalensis* at 50ka BP, the former's more gracile features suggest an earlier adoption of cooking; Neanderthals at c.200ka, when *H. sapiens* first started cooking, probably did not cook regularly, otherwise effects of this would be visible in later morphologies. However, I address instead whether Neanderthals c.100-40ka cooked as a later adaptation, as by this time fire is well-indicated at their sites, and no evolutionary consequences of this would have emerged by the time they went extinct.

Indications of cooking could be provided by burnt animal bone. As seen in Chapter Three, 111 out of 232 sites (48%) contain burnt bone. This is not necessarily associated with cooking however; bones can be burnt in other ways, including by chance in underlying sediment, or thrown (defleshed) into hearths as fuel or waste disposal. Several such sites also had negligible quantities of bones burnt, and the authors do not think that this represents cooking: Jonzac (Niven et al. 2012), Les Pecheurs (Moncel et al. 2008), Mujina Pecina (Miracle 2005) etc. Certain Neanderthals deliberate burnt bone as major fuel sources; most notably at El Esquilleu (Yravedra and Uzquiano 2013). If too few bones are burnt on a site, this appears accidental, and if too many, systematic post-consumption disposal as waste or fuel is indicated. Furthermore, when fleshed bones are cooked, they rarely burn as the meat insulates them (Koon 2006, Koon et al. 2004) – fully carbonised bone suggests pre-combustion defleshing. Conversely, cooking pre-defleshed meat would not burn bones at all. Occasionally though, deliberate cooking is better-attested. Instances where epiphyses (containing less meat) are more burnt than the shaft, suggests that fleshed bones were exposed to the fire, as at Misliya Cave (Yeshurun et al. 2007). In other cases, bones are burned in multicoloured patches (e.g. Kaldar Cave – Bazgir et al. 2017), again consistent with burning when fleshed. There are no plausible explanations for this aside from deliberate cooking.

Other heat-altered foodstuffs occur at Neanderthal sites. Neanderthal teeth from Shanidar (Iraq) and Spy (Belgium) contain heat-altered starch (Henry et al. 2011), although this may also result from age- or chewing-related degradation (Collins and Copeland 2011). Dental calculus also contains "altered" potentially-cooked fat in the Qesem and El Sidron Neanderthals (Hardy et al. 2012). Carbonised pounded pulses are present at Franchthi and Shanidar caves (Kabukcu et al. 2023), and charred plant seeds at Amud (Madella et al. 2002), Douara (Matsutani 1987), Franchthi Cave (Hansen 1991, Kabukcu et al. 2023), Gorham's and Vanguard Caves (Barton

2000), and Kebara (Lev et al. 2005). Most occur sporadically, but the latter site contains over 4,000 charred legumes and nuts (Henry 2017). Whilst these were not conclusively cooked, and may result from burning dung (Aldeais et al. 2016), the vast quantity does imply deliberate cooking. Although this small sample is the only definitive evidence we have for cooking, much goes unnoticed. N-alkyl nitrile studies, such as those at El Salt, Abric del Pastor and Crvena Stijena (Jambrina-Enriquez et al. 2019) indicates the nature of burned fats which could have contributed to Neanderthal diets. It can categorise into plants v animals, terrestrial v aquatic etc., but cannot detect cooking v non-cooking. The current evidence strongly suggests that at least some Neanderthal groups cooked; it was an individual and group trait, although possibly not at the species level. Late Neanderthals had increasingly Broad Spectrum diets; these late Neanderthals may have been forced to cook tough, hard-to-digest plant materials. This is against the lack of fire trends over time in Neanderthals (see Chapter Three, p.101); perhaps increasing proportions of later fires were exclusively cooking fires?

Genetically, Neanderthals show mixed evidence for cooking. Unlike modern humans, Neanderthals did not have detoxification genes to guard against harmful effects of smoke and overcooked food (Aarts et al. 2016). They also had the TAS2R38 bitter taste perception gene we sometimes lack, which warns against toxins (Lalueza-Fox et al. 2009, Miller 2011), suggesting that they ate some raw potentially-toxic food. On the other hand, Neanderthals and *H. sapiens* do share certain “cooking genes” at population levels associated with lipid-related metabolic processes (Carmody et al. 2016), and lack carbohydrate metabolic processing genes important for wholly raw diets (Ibid). Genetics is as difficult to correlate with behaviours as morphology however, as late Neanderthal technologies would not manifest evolutionarily. However, the fact that these are at the population level, suggests that most Neanderthals may have experienced cooking, or else these traits would not have propagated.

Methods of Neanderthal cooking are completely unknown. Food is chemically altered at temperatures as low as 55-95°C (Bentsen 2013) – lower temperatures are needed for detoxification and drying, and higher ones for broiling, protein denaturation etc. (Wandsnider 1997). Cooking can happen in many ways, the simplest being exposing food near fully-burning hearths. This method is fully visual and can be easily monitored, but risks burning the handlers, as well as incompletely cooking the food. For this method, which is the most likely that Neanderthals used, slow-burning low-heat fuels like dung would have been optimal, and would allow cooking food to be left unattended for several hours (Braadbaart et al. 2012). Other woody fuels with these same properties would also be ideal. Importantly, food need not be fully cooked; modern Hadza people only cook tubers for short 5-minute periods to assist with peeling, but not to predigest the starch inside (Marlowe 2010). Neanderthals may likewise have partially cooked food, in order to confer some benefits but not others – this may have been intentional, based on cost-benefit analyses, or because they were simply unaware of further benefits of fully cooked food. These partially-cooked foods may be archaeologically invisible, or easily mistakable for raw food. Food can be pit-roasted, where it is buried with hot coals or rocks, either beneath hearths or hot embers, and later re-excavated. Many burnt Neanderthal lithics may attest to this practice. However, this non-visual transformation, like heat-treating buried lithics, requires prior experience to know precise timings, mental flexibility to understand unseen transformations, and complex language to teach this technology. Neanderthals may not have had these capacities, although they could certainly do direct-visual tasks. Pit-roasting is ideal for high-lipid meats (Wandsnider 1997), unlike the leaner wild meats and plants Neanderthals would have encountered.

Another method is heated rocks acting as heat vectors. The rocks are sometimes placed within large animals' abdomens to roast them (Wandsnider 1997), or sometimes to boil water as a further heating vector. Boiling removes bone grease and strips residual meat from bones (Lupo and Schmidt 1997). This extracts more energy per animal killed, by improving the meat's energy value and allowing consumption of more of it. This however involves container technology, which in pre-pottery prehistory involved skin-containers, sewing etc. There is no surviving evidence of Neanderthal container technology, and no evidence that they a) could understand containers or b) could practically create them. Placing such containers directly on fires risks burning and rupture, so heated stones would have been required. This technology is only noted from c.30ka BP (Bentsen 2013), thus only associated with *H. sapiens.* However, this may just be because earlier examples have not been sought, because of the assumed lack of Neanderthal cooking or container technology. Large quantities of burnt stones at certain sites may represent this technology; plunging hot rocks into cold water to heat it would certainly cause the thermal fracturing seen in many specimens.

Speth (2017) posits that, instead of thermal cooking, fireless Neanderthals fermented and putrefied meats to provide 'cooking' benefits (Wrangham 2009, Wrangham and Conklin-

Brittain 2003). Harmless toxins and enzymes of fermentation bacteria inhibit spoilage pathogens, including botulism, *Clostridium cotulinum* (Alakomi et al. 2000, Ray and Joshi 2015). Pre-digested putrified food has reduced masticatory and digestion costs, without cooking's costs of fuel, direct time investment and potential health costs of smoke. Speth argues that putrid meat is not inherently unhealthy, and that modern aversions to it are culturally learned rather than innate. Putrefaction processes could have been completely fireless, instead placing meat in underground pits (Jones 2006), or submerging them in bogs, rivers and shallow pools (Fisher 1995), such as that found near Schoeningen (Speth 2017). It is particularly useful where damp cave environments inhibit meat-drying preservation methods. Putrefaction is an inevitable process, unlike cooking which rarely happens naturally. Neanderthals could have obtained pre-putrified meat from scavenging carcasses, or from being unable to preserve meat by salting or smoking methods. To understand putrefaction from first principles is very easy, as a) the transition is entirely visual (and olfactory), b) occurs frequently in nature and c) is independent of any other technology. Thus this would involve much less complex technology than cooking. This process however would be more challenging in cold, glacial climates; where Neanderthals conversely would also experience difficulties in using fire. These Neanderthals may have eaten more unprocessed foods.

This putrefaction could artificially make Neanderthals appear to be carnivores. Ammonia loss, along with small amounts of cadaverine and putrescine, enhances rotten foods in ^{15}N; such enhancements also suggest that Neanderthals were top predators with highly carnivorous diets (Ibid). Cooking does not cause such enhancements. If Neanderthals only cooked or ate raw food, enhanced ^{15}N levels do indicate carnivorous diets, but if they ate some putrefied meat (either deliberately or from scavenging carcasses), with tubers, bark etc. forming much of their diet, enhanced ^{15}N ratios would still suggest wholly carnivorous diets. Cooked meat-based diets are not healthy, but raw or putrefied meat-based ones are. Western 'meat' (muscle only) lacks many vital nutrients including Vitamin C, but this is present in other organs (Clemens and Toth 2016, Harrison and May 2009). Cooking destroys these nutrients, but fermentation preserves them, and produces additional B-vitamins (Speth 2017). Fermentation may have helped wholly meat-eating Neanderthals to survive, although it may have been less useful to those relying on plant resources.

Neanderthals might theoretically be divided into two groups. Fireless ones, or those with limited fire, cooked infrequently. They ate few cellulose-rich plants, or starch-rich tubers, relying instead on raw or deliberately-putrefied meat. Had such groups encountered fire, they would have been unable to cook their food without suffering health problems or shifting diets. Fire-using Neanderthals however were able to cook, and thus broaden their diets to include more plant-based resources which could be pre-digested by heat. Their meats could now be eaten either raw, putrefied, or cooked, without any health problems arising. Neanderthals were certainly not obligate fire-users in relation to cooking, but evidence strongly suggests that they did cook in many locations, and that for some it was an integral survival mechanism. Their cooking most likely utilised open-fire roasting, although we cannot absolutely rule out other cooking forms. Nevertheless, that which is easiest is most likely.

V: Conclusion.

Having reviewed three different Neanderthal technologies in which fire is an integral component, patchiness and variability is a key pattern. None of these technologies are present in all or even most Neanderthal sites, and none exist at a species-level. Were Neanderthals then not behaviourally obligated to use any such technologies to survive? If they could non-thermally process food through crushing and putrefaction, this could substitute for thermal cooking; clothing, although currently unevidenced, could provide some warmth (Collard et al. 2016, Wales 2012), and superior night vision could supply the lack of light (Pearce et al. 2013). The only obligatory fire may have been for deterring predators; Neanderthals killed by predators however, including Grotta Guattari 1 (Rolfo et al. 2023), may represent defenceless, fireless societies. Other archaeologically-invisible benefits of fire include smoke signalling, landscape burning, site waste clearance and defrosting frozen meats. These were ephemeral (smoke signalling), or their archaeological signature are almost identical to other fire uses (burnt bones could be cooking, waste, fuel etc.). The fact that fireless Neanderthal groups did most likely exist (see p.86) indicates that fire was not essential. However, regardless of whether fire was essential for Neanderthals, its uses would have helped its users survive better than groups lacking it. Some modern humans using fire for lithic heat-treating, metalworking, agricultural clearance etc., increases their group fitness and also indicates that we as a species have these *potential* uses, even if individuals do not do some or any of them. Average Neanderthals *could* use all of the discussed technologies. A Neanderthal may not have known about, or directly used a technology to experience its benefits. In group settings, whilst everyone perhaps cooked, only one or two knew how to make hafting adhesive or heat-treat lithics, but distributed their products to all. Likewise, if groups ever traded, fireless groups may have received cooked meats from fire-using groups, valuing the effects of cooking without understanding or appreciating technologies behind it. Even individuals skilled in specific fire-dependent technologies may not have understood the mechanisms of change, but could still perform the technology. Something does not need to be intimately understood to be widely practiced.

Archaeology and especially prehistory is always a record of differential loss. Despite the risk of over-interpretating data, more sites originally used certain technologies than is evidenced there today. There is evidence for lithic heat-treatment in 5 sites; adhesive melting in 3 and burnt bone (potentially evidencing cooking) in 111. Thus, including sites evidencing more than one type, 117 out of 232 sites (50%) show evidence of some form of advanced fire technology. Although assuming that all burnt bone represents cooking, grossly overestimating that number, accounting for taphonomic loss would push the true numbers in the opposite direction. If we exclude those 46 fireless sites, the proportion of fire-using sites with these technologies increases to 63%. This indicates that many Neanderthals used fire for more than just heating and lighting, although the proportion using fire occasionally for that must remain high. Those practicing more advanced fire-dependent technologies may have optimised their subsistence strategies by optimising their fuel. I have previously indicated how different temperatures and ignition rates would be optimal for cooking, adhesive melting and lithic heat-treatment. Although these can be achieved on the same fire at subsequent staggered burning stages (Bensen 2013), separate specialised fires for each purpose also achieves this. Neanderthals used many hearths concurrently on a site (Henry et al. 1996, Riel-Salvatore et al. 2013, Spagnolo et al. 2019), perhaps attesting to smaller individual fires rather than large group ones. In this scenario, different hearths could be optimised for different tasks, provided that individuals within sites cooperated rather than pursuing individual agendas. In order to optimise fires, these can differ either in a) hearth preparation and structure, b) fuel type burnt, or c) fire-controlling behaviours (frequency of adding fuel, burning duration, extinguishing etc.). Neanderthals rarely utilised different, or indeed any, special hearth preparations, and fire-controlling behaviours are undetectable. Thus, only fuels burned can indicate these practices as a form of advanced fire use. This forms the basis of my next chapter.

Chapter Five: Neanderthal Fuel Selection and Pollen Bias.

The best way of determining Neanderthal proficiency with fire technologies is to examine their fuel use. This is not only to observe what was burnt, and how different fuels affect general fires or specific tasks, but also to compare this with a fuel's environmental availability, thus determining levels of choice and selection involved. I conclude that wood is by far the most common Neanderthal fuel and is thus my focus, since Neanderthals rarely burnt other fuels such as coal or dung (Allue et al. 2017). Looking at wood-fuel selection through ethnographic analogies, I suggest how Neanderthals could have gathered fuelwoods, and how long this may have taken. Shackleton and Prins (1992) posit the often-cited 'Principle of Least Effort', in which, for wood gathering, people indiscriminately gather firewood based on environmental availability, regardless of wood quality. Thus their "selection" is for ease of gathering rather than fire optimization. Ethnographic data and archaeological data however show extremely variable fuel gathering strategies; certain societies select their fuelwoods by availability, but others seek specific qualities. These specific qualities are discussed in detail, and found to vary according to the desired task, although certain traits are universally desirable.

However, even following the Principle of Least Effort, plants will not be uniformly exploited in proportion to vegetation cover *at a specific moment,* as if an area is continually harvested, differential deadwood production, plant regrowth rates, and branch sizes will determine gathering rates. I examine the difficulty of determining archaeological selection in prehistoric contexts, as there is little background environmental data against which fuelwood can be compared. Much environmental data is inferred from anthropogenic charcoal itself, implicitly assuming the Principle of Least Effort, and creating a paradoxical effect. Using Knight (unpubl.), I demonstrated that, when comparing charcoal and pollen records for several Iberian Middle Palaeolithic sites, certain genera are distinctly over- or under-represented in the fuel record. This chapter examines whether differential pollen production alone is sufficient to create these differences artificially, before the next chapter examines the related question of the similar role of differential charcoal production.

I: Neanderthal Fuels.

Although primarily burning wood, certain Neanderthals utilized other fuels (e.g. coal, dung, lichens – Albert et al. 2012, Karkanas and Kyparissi-Apostolika 2024, Rigaud et al. 1995, Thery-Parisot et al. 1996). Some Neanderthals may not have recognized burnable fuels as fuel, as some do not burn in nature and cannot be identified as fuels from first principles. Neanderthal toolkits would have been insufficient to exploit many fuels; most fossil fuels, for instance, are buried underground, limiting reliance to limited surface deposits. They may only have burned deadwood or smaller branches if they could not fell whole trees (Beresford-Jones et al. 2011). Nonetheless, Neanderthals may have used many more fuels than we can easily recognize archaeologically. Wood is well-known as a fuel, as charcoal produced is easily recognizable as such, distinguishable to the genera or even species level. Other fuels however leave more ephemeral traces. Neanderthals burning coal at Les Canalettes (Thery-Parisot et al. 1996) could only be determined from analyzing morphological deformation of charcoal, assuming the deformation happened before burning rather than through post-depositional processes. Burning dung can be determined by the presence of black isotropic organic materials (Simpson et al. 2003), dung spherulites in ash (Gur-Arieh et al. 2013), ^{15}N-enriched material (Steele and Daniel 1978), phytoliths with different refractive indices (Elbaum et al. 2003), and the presence of calcium oxide (Shahack-Gross 2011). Subsequent taphonomic processes destroy much, and more durable remains (phytoliths and burnt seeds) could equally easily have come from grass kindling (as at Gorham’s and Vanguard Caves – Gale and Carruthers 2000). Seeds burnt in dung or burnt in grass are indistinguishable, as they do not contain distinctive acid etching marks like ingested bone in faeces (Horwitz and Goldberg 1989, Smith and Botha-Brunk 2011). Even where dung or guano is found (e.g. Kebara - Goldberg and Bar-Yosef 1998) it is difficult to say whether it is anthropogenically or naturally introduced to the site. Thus when discussing these fuels (aside from wood), we must assume that their use was either as occasional innovations, or that finding more common usage relies on as-yet undeveloped scientific techniques.

‘Wood’ is the most common fuel in the Middle Palaeolithic and indeed throughout human history. ‘Wood’ here may refer to arboreal trees, either branches (sapwood) or main trunks (heartwood), or woody ligneous material from smaller bushes and shrubs (e.g. *Erica*). Other parts of plants may provide kindling (dry leaves, fungi or grasses), but the main sustaining fuels come from the wood itself. This extremely common resource varies in quality depending on genus and condition. It renews over short timescales (trees prune deadwood annually, and new trees mature in c.5-50 years), and usually can be extracted without any specialist tools. Seeing natural wildfires consume woody vegetation would lead to hominins inferring that wood is a fuel. Woody plants are also used for shelter construction and tool manufacture, and have edible fruits, which are also frequented by prey species. Thus woodlands are key general foraging areas. Wood availability varies by landscape; steppic Neanderthals with fewer woods locally (especially in glacial periods) may have depended on other fuel sources more. As a byproduct of fires or natural wildfires, Neanderthals may have burnt wood charcoal of course; however, this would be completely undetectable. Burning charcoal would fully combust the charcoal, and collecting it would be time-consuming and require container technology. Sufficient quantities would only exist in post-wildfire contexts, where unburnt wood can still be found (see Chapter Ten, p.286).

Fossil fuels are extremely common today, both for larger industrial processes and for smaller household fires. They are non-renewable (except over extremely long timescales), and are rarely environmentally-abundant, except for open-air coal outcrops or bitumen springs. Wildfires would not usually ignite coal, and it is difficult to see how Neanderthals could understand its combustible properties (as at Les Canalettes). Its superficial resemblance to charcoal, a byproduct of combustible wood and itself combustible, may have created this analogy. However, at Les Canalettes, use of coal anticorrelates with forest spread over time (Thery-Parisot et al. 1996), suggesting coal was a fallback fuel rather than one actively sought. Neanderthals also frequently used bitumen as a lithic hafting adhesive, at Umm el Tlel (Boeda et al. 2008a,b), Campitello (Mazza et al. 2006), Inden Altdorf (Pawlik and Thissen 2011), Hummal (Hauck 2010) and Gura Cheii-Rasnov (Carciumaru et al. 2012). However, given bitumen is flammable, igniting at c.400°C (Lukyanova et al. 2019), Neanderthals could theoretically have observed its combustion, while it was melting as an adhesive, and burnt it; however, high ignition temperatures and toxic fumes would have made burning it highly unpleasant. In general, fossil fuels, aside from occasional surface deposits, are buried underground, and would have required specialist extraction tools for exploitation that Neanderthals did not possess.

Bone may have been an important fuel for certain Neanderthal groups, especially in areas of wood shortage. Given Neanderthal reliance on consuming megafauna, bone was a frequent waste product; although often split to access the inner marrow (e.g. at EDAR Culebro 1 – Yravedra et al. 2014), the remains were still a valuable fuel source. Bone burns well, reaching temperatures of c.540°C (Glazewski 2006); however with a high ignition temperature. Unlike woods which is ignitable from kindling alone, bone requires hot-burning (wood-fuelled) hearths to start burning, releasing energy at that point. No fire could be 100% bone-fuelled. Burnt bone, as mentioned in Chapter Two, results from its use as fuel, as waste disposal, and in cooking. Whilst cooked bone is unlikely to be confused with fuel-bone (the latter being fully calcined and the former being burnt in mottled patches depending on the placement of meat on it), and bone accidentally buried beneath hearths would also be only partially-burnt, bone intentionally burnt as either fuel or waste disposal would display identical characteristics, being fully white and calcined. The difference therefore is the setting; odd fragments of bone in otherwise wood-fuelled fires with surviving charcoal suggests burning of waste bone, whilst abundant bone and minimal charcoal suggests bone-fuelled fires. These have been discovered in Abric Romani and El Esquilleu (Courty et al. 2012, Yravedra and Uzquiano 2013); however, these are rare. This is surprising given that Neanderthals so commonly killed large prey and could have accessed large quantities of waste bone.

Finally, Neanderthals may have burnt animal dung. This substance would have been widely available if Neanderthals lived close to large ruminant herds, as suggested by their prey profiles of large prime-age herbivores (e.g. Richards et al. 2008). Dung is highly renewable, and cannot be over-exploited unlike other resources, unless the animals themselves are driven to extinction (Sillar 2000). Most modern ethnographic studies focus on agriculturalists or pastoralists (e.g. Anderson and Ertug-Yaras 1998, Deckers 2011, Winterhalder et al. 1974), who keep their own animals, and have distinct penning or sheltering areas where dung concentrates. Shahack-Gross (2011) argues that dung-burning was uncommon before pastoralism, which I generally agree with. However, given the abundance of large herbivore prey and their obvious proximity to Neanderthal communities in mammoth steppes, their dung could easily have been collected if desired. Furthermore, dung can spontaneously combust due to heat internally released from decomposition and cellulose oxidation (Mlukuz 2009); this would indicate to Neanderthals that this was a viable fuel. Different dungs have different qualities; modern people prefer cow to sheep dung for instance as the former burns hotter, gives longer-lasting embers for reigniting fires, and lacks the latter's acrid smoke (Cardoso et al.

2012, Mlukuz 2009, Winterhalder et al. 1974). However, occasionally sheep dung is favoured, as it contains less unprocessed organic matter and burns more slowly (Anderson and Ertug-Yaras 1998). No research has been carried out on mammoth or woolly rhino dung, as obviously experimental materials are no longer available. Modern elephant dung is burnt as a fumigant (Dubost et al. 2021, p.6) and can be made into biofuel briquettes (Mainkaew et al. 2023), but is not widely used ethnographically. Given the animal's morphologies and diets however, modern cow dung may provide the best analogy, providing similar levels of undigested plant matter (Ibid).

Burning dung produces abundant smoke (Pena-Chocarro et al. 2005, Zapata et al. 2003) – a disadvantage for domestic fires, but excellent for fumigating areas and removing pests, smoking meats or hides, or creating smoke signals. Consequently, in modern contexts dung is most frequently burnt outdoors (Asouti 2013). Dung fires have much smaller void spaces than wood-fuelled fires, so less air penetrates and the fire burns more slowly (Braadbaart et al. 2012). This would have caused lower temperatures than in wood fires, but fuel lasted longer, requiring smaller collection costs. Lower temperatures may also have been better for cooking and minimizing burning risk. Conversely however, Winterhalder et al. (1974) found that 3h fires required 15.4kg of dung but only 11kg of wood. Whilst dung burns more slowly and evenly than wood, its lower calorific content compared to wood may somewhat negate these advantages, creating requirements for similar overall fuel quantities. Dung worked into cakes with straw and water creates a much more efficient fuel that can attain higher temperatures (Charles 1998). Rhode et al. (1992) studied high-altitude Tibetan pastoralists, cold conditions simulating Middle Palaeolithic Europe. Here, a single fire requires 100-150 litres of dung chips per day in the summer, and double in the winter, using 70,000-80,000 litres of dung annually. Rhode calculated annual foraging requirements of 320 person hours, based on yak dung being spaced 3-4 paces apart in grazing meadows. This is under an hour a day, plus additional drying time; however, Palaeolithic herds would probably have been further from home bases than Tibetan herds, requiring additional travel time to the location. The herds would also have been wild and dangerous unlike yaks, preventing Neanderthals approaching as closely to harvest the dung. Furthermore, collecting semi-liquid dung would require containers, which Neanderthals may not have possessed. This would have limited them to pre-dried dung, which may be spaced further apart and take longer to find, although saving on additional drying time.

II: Principle of Least Effort.

In 1992, Shackleton and Prins published an influential paper positing the 'Principle of Least Effort' hypothesis, in which resources are gathered using minimal effort. Individuals select resources closest to their central dwelling/home base, regardless of whether this resource is optimum for the task required, provided that it functions. So, therefore, if someone wants a handaxe, they choose nearest available stones, regardless of quality, provided that it is at all knappable into desired shapes. In opposition to this, those who do not conform to the 'Principle of Least Effort' travel further for desired resources, ignoring inferior closer ones. This provides higher quality materials at higher foraging costs, deliberately saving closer resources for other times. This allows long-term resource sustainability through uniform foraging, and leaves nearby resources for harsher seasons when travel costs are higher.

Whilst the Principle of Least Effort applies to many resource types, it particularly applies to uniformly-distributed resources like fuelwood. Although fuelwood is sometimes in stands, it is generally more uniformly distributed across the landscape than lithics or prey – see Figure 1. Collecting firewood is labour-intensive, requiring many daily foraging hours, although this varies by latitude and altitude (Turker and Kaygusuz 2001). Large continuously-lit hearths need 50-100kg of firewood per day (Gowlett et al. 2012, in Pryor et al. 2016), and fuelwood collection takes up to 6 hours, covering up to 13km (Ibid, Nagothu 2001). This of course varies immensely by landscape type, and each ethnographic reference study is bound to one particular landscape. Firewood is particularly bulky compared to fossil fuels, requiring high collection times for values received. Reducing foraging times would increase time for other activities. Conversely, higher-quality wood would make using fire easier during burning sessions. Selection or random procurement in fuelwood gathering depends on whether selecting superior fuels outweighs additional collection costs.

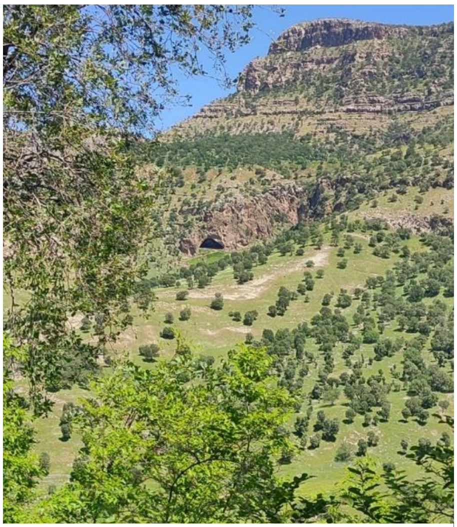


Figure 5.1: The (modern) landscape around Shanidar Cave, Kurdistan. Although there are a few open spaces, it represents an area of mostly uniform wood-fuel distribution where the Principle of Least Effort could apply, although this may have been different in the Middle Palaeolithic. Photograph: Michael Hitchcock.

Selection mitigates resource diminution and fuelwood stand exhaustion. Following the Principle of Least Effort, individuals must travel increasingly further afield as nearby resources are exhausted. After a certain radius, consumption is balanced by natural fuelwood replenishment within this radius, and supply equals demand; however, this radius is larger than ideal. If all individuals foraged according to wood quality, preferring certain genera or traits, they consume wood in these categories, and less-preferred fuelwoods remain at high levels. Individuals must then either forage for suboptimal fuelwoods closer to home, or travel increasing distances for preferred fuels at higher gathering costs. In a third scenario, the community divides into those selecting for specific traits, and those following the Principle of Least Effort. Within a small radius of the settlement, preferred fuelwoods would be exhausted by both groups; the selective group would travel further afield for preferred fuelwoods, whilst others forage locally for less-preferred fuelwoods. Here the fuel consumption burden is split: both locally, and preferred genera over wider areas, will be less-intensively harvested than in either of the previous scenarios, thus making both more available. Individuals could of course combine foraging fuelwood with foraging for plant foods; certain plants have fruits (e.g. *Prunus*), others have nuts or seeds (e.g. *Castanea, Pinus*) and these would be sought both as fuelwood and as a food resource.

Shackleton and Prins clarified that the Principle of Least Effort is not uniformly applied to wood collection, and that many [*H. sapiens*] societies do actively select for particular traits. The Principle of Least Effort is particularly important in areas of low fuelwood availability and high population numbers on permanently occupied sites; in other scenarios, the Principle of Least Effort is not employed (Shackleton and Prins 1992, pp.633-634), such as in comparative Himalayan studies (Samant et al. 2000). Nonetheless, many believe the Principle of Least Effort is the default unless there are compelling reasons otherwise. Many authors do not explicitly state this principle in their works, implicitly assuming it (e.g. Chabal 1988, 1992, 1997, Chabal et al. 1999, Prior and Price-Williams 1985). This can harm environmental reconstruction methods. However, most papers distinguish between opportunistic and active selection. I found 50 papers noting opportunistic fuel procurement, and 50 noting non-conformity with environmental availability for fuelwood, suggesting selection either for genus, traits or condition (Table 5.1 beneath). Although an incomplete sample, this sufficiently demonstrates that the Principle of Least Effort is by no means universal.

Table 5.1: A comparison of studies where Opportunistic Procurement and Active Selection of fuelwoods have been suggested. This shows that no one model prevails across a single region or period.

Opportunistic Procurement		**Active Selection**	
Era	**References**	**Era**	**References**
Middle Palaeolithic	Uzquiano et al. 2012	Middle Stone Age	Allott 2006, Lennox and Bamford 2017, Lennox et al. 2017
Upper Palaeolithic	Aura et al. 2005, Bergueda 1998, Beresford-Jones et al. 2011, Caracuta et al. 2020, Mir and Freixas 1993	Late Stone Age	Beldados et al. 2022
Mesolithic	Alcolea et al. 2017, Austin 2009, Carcaillet 2017, Gracia 2017, Monteiro et al. 2017	Mesolithic	Alday 2007, Bishop et al. 2015, Ruiz-Alonso and Zapata 2015
10,000-2,000BP (Brazil)	Bachelet and Schell-Ybert 2015	10,000-6,000BP (Argentina, Chile, Egypt)	Ferme and Civalero 2019, Joly et al. 2017, Marston et al. 2017
Neolithic	Asouti 2003, Chabal 1997, Gomez et al. 2021, Jansen and Nelle 2014, Kabukcu 2015, Ntinou and Tsartsidou 2017, Out 2010, Poggiali et al. 2017, Watkins 1996	Neolithic	De Carle 2014, Delhon et al. 2017, Dufraisse 2008, 2012, Liu et al. 2022, Schroedter et al. 2012, Thiebault 2001
5200-1500BP (China)	Li et al. 2017	Chalcolithic	Coradeschi et al. 2023
Bronze Age	Jakobitsch et al. 2022, Jude et al. 2016, Marston 2009, Moskal-del Hoyo 2012, Moskal-del Hoyo et al. 2010, Willcox 1999	Bronze Age	Figueiral 1995, O'Donnell 2016, Ponomarenko et al. 2020
Iron Age and Roman	Baines 2019, Gur-Arieh et al. 2014, Heiss and Oeggl 2008, Jorda et al. 2008, Salisbury and Jane 1940	Iron Age and Roman	Becker et al. 2020, Godwin and Tansley 1941, Martin-Seijo and Vila 2019, Rovira and Chabal 2008, Sadori et al. 2010
Roman	Deforce and Hanca 2012, Figueiral et al. 2010, 2017	2000BP (Argentina)	Ortiz et al. 2017, Pasqualini et al. 2016
From 2500BP (Australia)	Byrne et al. 2013	Medieval	Deforce et al. 2013, Knapp et al. 2015, Py et al. 2013, Wheeler 2011
1200-700BP (DRC)	Hubau et al. 2013	1200-250BP (Brazil)	De Azavedo and Scheel-Ybert 2020

Opportunistic Procurement		Active Selection	
Era	**References**	**Era**	**References**
Medieval	Buonincontri et al. 2020, Martinez et al. 2023	500-200BP (Alaska)	Crawford 2020
1440-1820 (Hawaii)	Kolb and Murakami 1994	Maya	Dussol et al. 2016a,b
1900-2000 (Tierra del Fuego)	Pique 1999	200-100BP (Caribbean, Polynesia)	Bodin et al. 2021, Huebert et al. 2010
Ethnographic	Picornell-Gelabert et al. 2011, Toffin and Wiart 1985	Ethnographic	Henry and Thery-Parisot 2014, Jiminez-Escobar and Martinez 2018, Kegode et al. 2017, King and Dotte-Sarout 2019, MacDonald et al. 1998, Zapata Peña et al. 2003
Theoretical and Methodological	Asouti and Austin 2005, Dufraisse 2014, Shackleton and Prins 1992, Thery-Parisot et al. 2010, Zipf 1949	Theoretical and Methodological	Botha et al. 2024, Delhon 2018, Dincauze 2000, Dotte-Sarout et al. 2014, Pique 1999

Importantly, all these aforementioned examples (except Uzquiano et al. 2012) are from *H. sapiens* of different eras. All these individuals are cognitively-modern, and all thoroughly proficient with fire. Pre-human species lacking active selection cannot automatically suggest they lacked cognitive modernity. However, active selection certainly suggests proficiency with the technology concerned. Non-hominin species also practice active selection (e.g. prey choice - Machovsky-Capuska et al. 2016), and selection cannot automatically be considered a trait of cognitive modernity. However, as wood burning traits are not immediately obvious without testing them (see Chapter Nine), selection of wood optimized for particular functions suggests previous (experimental) fire use over time, in order to have reached that current level of selectivity.

III: Ethnographic Fuel Selection.

Reviewing modern ethnographic literature on fuelwood procurement can provide insights into Neanderthal behaviour. However, ethnography of course deals with *H. sapiens* rather than *H. neanderthalensis.* The behavioural capacity of one AMH group is parallel to that of another; if one group attributed certain superstitions or arbitrary attributes to certain fuelwoods and consequently deliberately choosing or avoiding them, the other group could *theoretically* do likewise, even if they didn't practice those traits. However, we do not know whether Neanderthals had abstract thought, and we cannot assume any non-tangible factors in their wood selection. Secondly, most modern ethnography deals with settled agrarian populations, despite increasing research on hunter-gatherers (e.g. Henry et al. 2018, McCauley et al. 2020, Thoms 2008). Not only are agrarian people permanently settled in one spot, causing different resource stresses to nomadic people, but landscapes are often in individual or community ownership and subject to particular property or use-rules from which hunter-gatherers, and Neanderthals, are generally free. Thirdly, fuelwood collection is frequently a gendered activity today, often undertaken by women and children in Indian societies (Bhatt and Sachan 2004), Inuit (Steelandt et al. 2013), Maasai and Malawi (Biran et al. 2004), Ugandan (Tabuti et al. 2003) and the Moroccan Jebala (Zapata et al. 2003). This is because in these areas women control the domestic sphere, including fire and fuel procurement. However, Patagonian people collect fuel independently of gender (Cardoso et al. 2012), and males dominate Brazilian fuel collection (Ramos et al. 2008a). In the latter, women stay at home while men go to work, collecting fuel on their travels. Although the norm is women and children, this variety means that we cannot definitively say which gender collected fuelwood. Furthermore, we see no 'gendered Neanderthal roles', except perhaps more female Neanderthals working materials with their teeth, indicated by higher incidences of tooth wear in females (Estalrrich and Rosas 2015). Neanderthals may not have conceptualized gendered roles, which also depends on living in household units, where one member creates and maintains fire to benefit many. Neanderthals may instead have had small, personal fires (Spagnolo et al. 2019).

Nonetheless, ethnography provides valuable analogies, and can help understand past fuelwood gathering. Quantities gathered on foraging trips could indicate Neanderthals fuel requirements. Smaller families consume more fuel per capita than larger ones (Marufu et al. 1997) as one fire serves many people. However, as Neanderthal family structure and numbers using each hearth are unknown, I calculate per hearth rather than per capita consumption. The large 1m hearths at Beeches Pit needed 50-100kg of firewood per day to maintain (Gowlett et al. 2012, in Pryor et al. 2016), and 18250-36500kg per year. Viking Iceland, with climates close to Middle Palaeolithic Europe, had birch fires burning at 2.28kg/h (Trbojevic et al. 2011). Fires in hotter climates being used exclusively for cooking consume less fuel; 5-25kg per day in Tanzania and Malawi, just 6kg in the Maasai (both Biran et al. 2004), and 5-7.5kg per day in Uganda (Tabuti et al. 2003). Although we do not know explicitly whether Neanderthals cooked, fire was important for heating their camps, so we must assume the higher wood consumption of colder climates. This also assumes that their fires were constantly lit, which would be unnecessary if fire-starting technology was mastered. Given their transhumance, Neanderthals could have lit fires at the start of a site's occupation to cook food brought with them, warm the area, and destroy vermin or pests that had infested the site since its last use. Thereafter, fire may have been used infrequently for subsequent warming or cooking, and then only by necessity for fumigation and cooking at their next site.

50-100kg per day may be the maximum realistic amount a fire could have needed, with the actual amount being much smaller. The number of Neanderthals using this fire is unknown; if everyone clustered around one fire, using it minimally for technological processes and mostly for warming the area, then one fire may have sufficed for the whole group, which could have been 10-30 individuals (Davies and Underdown 2006). However, given that ten people is the realistic maximum around a single fire, each individual would have provided 5-10kg of wood every day (assuming all contributed equally). But fires were probably much smaller; small sleeping hearths at Abric Romani, L'Oscorusiuto, Riparo Bombrini and Tor Faraj (Henry et al. 1996, Riel-Salvatore et al. 2013, Spagnolo et al. 2019) may have been individual, or for single family units of 2-3 individuals. It is more probable that individuals would have individually contributed 25-50kg of wood each day, although these 'personal' fires were smaller than those at Beeches Pit, so towards the lower end of that scale.

How long would this gathering have taken? In India, yearly fuel collection time is 34-504 hours, with a mean of 190 hours (Heltberg et al. 2000). However, ethnography's weakness is that each landscape is unique. Wild landscapes are generally more treed than farmland, although not necessarily Middle Palaeolithic steppic landscapes (Richter 2006). A more helpful comparison is that adult Maasai wood foragers carry around half their body weight in wood (Biran et al. 2004). Given Neanderthals males weighed c.78-83kg, and females 63-66kg (Froehle and

Churchill 2009), either sex could have carried enough wood in a single trip for the entire day. Modern Ugandan fuelwood loads are 15-20kg (Tabuti et al. 2003), and Neanderthals could have carried more. These weights are however dependent on being able to carry wood bundles strapped to the head (Biran et al. 2004). Neanderthals could have used the cords found at Abric du Maras (Hardy et al. 2020) for this purpose; if not, their limitation would not have been weight, but instead how much they could carry in their arms. If they did conduct specialist gathering expeditions, wood would have been carried alongside lithics and prey, further reducing their carrying capacity. They may have cached wood at various points along their daily path, to collect later.

Wood is collected in many different ways; sometimes cut directly from living trees (e.g. the Maasai - Biran et al. 2004); sometimes entire trees felled by burning through the roots to bring it down (as with the Californian Yokuts – Gayton 1948, in Pryor et al. 2016), and sometimes ropes thrown over higher branches and pulled to break them off (Blackfoot Indians – Ibid). People most frequently use deadwood, either detached on the ground, still attached to living trees, or entire dead trees (snags). Deadwood gathering is ethnographically common in Malawi (89% of all wood gathered), the Maasai, Uganda (55% collected dead branches, 22% felled standing snags) and Patagonia (Abbot and Lowore 1999, Cardoso et al. 2012, Jensen 1984, Tabuti et al. 2003). Archaeologically, burning deadwood is seen in the Cabecho da Amoreira shell-midden (Monteiro et al. 2017), Krems Watchtberg and Pavlov I (Damblon 1997, Pryor et al. 2016), Çatalhöyük (Kabukcu 2017) and among Neanderthals at Abric Romani and El Salt (Vidal-Matutano et al. 2017). Archaeologically, deadwood fuels are evidenced by tunnels and holes from wood parasites, and fungal degradation of charcoal cell walls (Cichoki et al. 2014), though these also result from storing and drying wood.

Deadwood collection does not harm living trees, allowing future deadwood or fruit production; moreover it frees up timber better employed in construction or toolmaking. Fallen branches are often already pre-dried for burning. Fuelwood storage is extremely constraining for nomads (Thery-Parisot et al. 2010), thus choosing deadwood and quick-drying fuelwoods partially helps solve this issue. Deadwood is also generally small-diameter sapwood rather than heartwood, being twigs or branches rather than main boughs or trunks. In the Neolithic at Chalain, the wood burnt was <10cm diameter (Dufraisse 2008), c.5cm in Iron Age Tyrol (Heiss and Oeggl 2008), 2-5cm in Bronze Age Iberia (Garcia-Martinez and Dufraisse 2011) and 0.5-2cm in

Patagonia (Cardoso et al. 2012). Using such small wood is less efficient, as it is more unwieldy and less weight can be carried per volume unit bundle. Smaller pieces also burn quicker, attaining higher temperatures with more oxygen availability, but requiring more fuel overall for given burning periods. Due to increased oxygenation of this burning, less charcoal forms from smaller pieces than from larger trunks.

Riverine driftwood is an important additional fuelwood source. Deadwood falls into river systems, to be deposited at specific shallower bends. This wood is already downed, debarked and often pre-dried for immediate burning (Venes 2002). Water flotation processes also preferentially preserves high quality seasoned wood, as damaged, decomposing woods sink upstream (Alix 2005). Driftwood gives out less heat than standing dry wood (Ibid), although this difference is negligible (Alix and Brewster 2004). Driftwood can be found in predictable spots near harvestable river cobbles, and away from dense tree stands with limited biodiversity for generalized foraging. Riverine cobbles have been utilized for tool manufacture by Neanderthals at Bordes-Fitte (Aubry et al. 2012), Cioarei-Borosteni (Carciumaru et al. 2002), Orgnac 3 (Moncel et al. 2012) and Karabi Tamchin (Yevtuskenko et al. 2003). This supply is however often extremely seasonal, only abundant in spring post-snowmelt (Wohl 2013), although debris jams in certain rivers provide constant supplies (Pryor et al. 2016). Within driftwood-selecting communities, some such as the Greenland and Kodiak Inuit select by condition rather than by genus, and some like the Kobuk Inuit are unselective within driftwood caches (Shaw 2012, Thery-Parisot 2002). Condition can be determined by looking for dryer pieces floating higher in the water; listening to the sound logs emit when hit can also determine dryness to experienced listeners (Shaw 2012). The nature of driftwood however, separated from its parent tree, means that unless different de-barked branches have distinctive morphologies, selection by fuelwood genus is difficult.

When collecting wood, the distance travelled is dependent on the availability of local vegetation; the Evenk only travel 250-800m (Henry et al. 2009), Ugandan people travel under 2km (Tabuti et al. 2003), Aborigines go up to 5km (Bird et al. 2008, Tindale 1974, p.65) and Inuit people up to 13km (Stefansson 1919, p.45). Neanderthal journeys may have been as little as 3km (Verpoorte 2006), though in treeless landscapes, they could have journeyed as far as the Inuit; it is unlikely to have been further.

If Neanderthals collected enough fuel to sustain small personal fires and had little division of labour, they would have gathered up to 25kg of fuel each day. For this, they would have travelled up to 10km, as is consistent with arboreal-scarce landscapes, foraging for 1-2h each day, a considerable effort for this technology. This time is similar to if they had collected animal dung, neither option representing much lower foraging efforts. When collecting, they probably focused on pre-dried deadwood, saving the effort of felling entire trees (Beresford-Jones et al. 2011. They may have actively created this deadwood by girding or ring-barking trees on previous trips to kill them (Pryor et al. 2016). In addition, they may also have exploited driftwood in riverine systems, where they would have also collected riverine cobbles for tool manufacture. By collecting deadwood, their fuel may have come in many smaller-diameter pieces, which required cordage technology (rope or leather straps) to bind together, and would have also burnt faster at higher temperatures. It remains to be seen, within this pool of easily-accessible deadwood, whether Neanderthals would have additionally targeted specific genera, either through direct identification and choice, or through indirect association with particular traits (low ash content, low smoke content, density etc.) associated with a particular genus.

III.I: Traits selected for in “good” fuelwoods.

The notion of “good” fuelwoods is extremely subjective, and dependent on many factors. A key one is the intended function of the fire. General-purpose fires may require very different woods to ones required for specific functions such as cooking. Slow-burning woods are widely valued, as fewer new pieces must be added to the fire (Picornell-Gelabert et al. 2011) – particularly important if fires are kept burning overnight. Denser fuels burn more slowly; however, if overall calorific contents of two woods are identical, they must emit identical amounts of energy when burned, over whatever period. Denser, slower-burning woods therefore emit less energy (heat or light) at any given time compared to less-dense, faster-burning woods. For instances requiring shorter-lived bursts of more intense heat (such as metalworking), faster-burning woods are valued. Higher amounts of heat or light could cause discomfort in enclosed spaces (including Neanderthal caves), making it difficult to manipulate wood or food onto or off fires.

A lack of smoke is a highly valued fuelwood trait, especially when burning in enclosed spaces. Acrid smoke irritates the eyes and lungs (Winterhalder et al. 1974), causing harmful long-term carcinogenic effects (Bolling et al. 2009, Brouwer et al. 1996). Smoke mostly depends on a wood's moisture content (Tihay-Felicelli et al. 2017); this varies by genus/species, but overall depends on the wood's condition (green or dry) and the amount of extractives (non-structural lignocellulose components) in it. Whilst smoke is generally unwanted, certain applications value it, such as creating smoke signals, repelling biting insects and smoking meats/fish. For the latter in particular, the quality as well as the quantity of smoke is important; certain genera such as alder, crabapple, poplar and willow have smoke which imparts a good flavour to smoked food (Bishop et al. 2015, Henry et al. 2018), others such as oak smoke has preservative qualities (Bishop et al. 2015), whilst conifer and birch smoke, which gives food bad flavours, are avoided (Henry et al. 2018). Conversely, for smoking hides, Evenki people use rotten larch, which is rejected for food-smoking (Ibid). Thus, even when selecting for a particular trait (smoke), the specific task for which this trait is selected is important.

Related to smokiness and the wood's condition, wood drying time is an important criterion. Quick-drying woods are universally preferred; even if gathered when green, quick drying times give flexibility in how to use a fuel. Strongly-nomadic Neanderthals (e.g. Richards et al. 2007) would not have used particular camps for long. Whilst Neanderthals could have stored wood to dry at a camp for them to return to and use another season, the ability to dry wood over a shorter single occupation would be invaluable.

Finally, an important criterion only infrequently mentioned by ethnographic participants, is calorific fuel value. This value both determines energy potentially emitted by given quantities of fuel, and also quantities of fuel needed to maintain certain temperatures/burning durations. Naturally, higher calorific values allow higher temperatures to be theoretically reached, assuming similar burn times, and less fuel has to be carried assuming similar burning rates. However, fuelwood genera vary little in basic calorific value, from c.19.6-20.5MJ/kg (Senelwa and Sims 1999), with a maximum range of 3.35MJ/kg (Chabal 1997). My analysis (Chapter Seven) shows slightly more variation (14.5-22.2MJ/kg, p.189). Higher lignin and extractive contents increase calorific values (Dermibas 2001, 2017, White 1987), and higher unburnable ash contents lower values. However, higher ash contents are occasionally valued in fuels, as it creates glowing embers after fires (Tabuti et al. 2003, Tietama et al. 1991). These serve both to bake food in, and to reignite fires left glowing overnight without needing to utilize more pyrotechnic technology. Other factors affect calorific content however. Different parts of plants have different calorific values; heartwood has higher calorific values than sapwood, and both are higher than bark (Shanavas and Kumar 2003). In conifers however, resin has the highest calorific value at 40.1kJ/g (Ivask 1999). Dense woods are valued, as smaller volumes of denser woods must be burnt than less dense ones. Wood density, as aforementioned, also strongly correlates with burning duration and speeds of heat release. Density increases throughout a tree's life, and older stands have denser wood than their younger counterparts (Wasik and Michalec 2012). Increased moisture content likewise decreases calorific value, as energy must be expended to evaporate the free water before combusting the wood, reducing the net gain. Green woods have lower calorific contents than dry woods; wood is greener in spring, correlating with blooming periods and frequent rain (Autengruber et al. 2020, Nunez-Regueira et al. 1996).

IV: Evidence for Neanderthal Fuel Selection.

In my Masters' thesis (Knight unpubl.) I compared charcoal and pollen records of ten levels within five Iberian Neanderthal sites, dating from c.91-28ka BP. I studied whether Neanderthals were selective in their fuel use, through comparing anthropogenic charcoal records with corresponding background pollen records of the various genera. This study however omitted three main factors:

- Whether pollen reliably indicated background vegetation, or whether, through differential production, diffusion and degradation rates, certain genera are under- or over- represented in this regard.
- Whether genera apparently selected for or against are best explained in terms of intrinsic fuel quality, or whether natural factors such as deadwood production rates and stand regeneration better explain these discrepancies as part of the Principle of Least Effort.
- Whether proportions of each fuel being burned faithfully translated into proportions of charcoal we find today, or whether different genera have differential charcoal production rates, or survival rates. The first question is addressed in this chapter, whilst the latter two forms the basis of the next four chapters.

IV.I: Methodology.

In this study, I used data from Abric Romani (Allue et al. 2017, Burjachs and Julia 1994), Cova de Coll Verdaguer (Daura et al. 2017), Cueva del Camino (Arsuaga et al. 2012), El Esquilleu (Uzquiano et al. 2012) and Gorham's Cave (Carrion et al. 2008). All these sites are caves or rockshelters, allowing much better preservation of both anthropogenic and environmental data than open-air sites. A brief archaeological description of each is given in Appendix Two. However, caves may act as pollen filters, excluding large amounts of it. Moreover, as outlined in Chapter Three, Neanderthal cave and open-air sites may have used fire differently so that these findings can only be applied to cave-using Neanderthals. The number of these sites were severely constrained by needing to have detailed pollen and charcoal data from the same archaeological strata. Other Iberian sites including charcoal data, but as yet without pollen data include Abric del Pastor, Abrigo de la Quebrada, Cova Gran, Cueva Anton, El Salt and Gruta Oliveira (charcoal from Vidal-Matutano et al. 2015, 2018, Carrion Marco et al. 2019, Allue et al. 2018, Zilhao et al. 2016, Badal et al. 2011).

When possible, within a single layer, charcoal and pollen records were directly compared to allow fine-scale analysis over short periods. Ideally, individual fire features would have been analysed; however, most sites do not contain discrete fire features, and commingled charcoal features are much more common. Whilst this analysis does not show individual variation and choice, it does provide averages of what groups burnt, overcoming issues of seasonality and different hearth functions. Thus in certain cases, multiple hearths within a layer were combined to form averages. Likewise, combining multiple stratigraphic layers of charcoal allowed direct comparisons with longer-scale climatic pollen diagrams from these same sediments. This combination of stratigraphic levels was not optimal but necessary for direct comparison, and remained within similar climatic and chronological time periods. Charcoal was only noted to the genus level due to difficulties and inaccuracies of identifying species. This meant that sometimes, where species had been ascertained (as in *P. sylvestris*), multiple species tallies within a genus were combined (e.g. to *Pinus*), allowing comparisons between genera and sites. Some charcoal was either unidentifiable, or described only to the family level, and was thus rejected (total percentages excluded are noted beneath each table). Likewise for pollen, those described only to the family level, or those genera which were not viable Neanderthal fuels or do not produce charcoal were rejected. Percentage totals were tallied from the remainder.

Similar direct pollen-charcoal comparisons focusing on fuel selectivity have been undertaken before, by Monteiro et al. (2017), Newman et al. (2007), O'Donnell et al. (2017), Ruiz-Alonso and Zapata (2015), Stuart and Walker (2018). A critique of all charcoal-pollen comparisons is that they are unsuitable for direct comparison, being subject to different biases and coming from different scales. Anthropogenically-introduced charcoal (as opposed to windblown particles) derive from as close to the cave as possible (within 100m), whereas pollen represents more regional trends – different vegetation types in these two catchment zones mean that they represent entirely different scales (Carcaillet et al. 2001). However, this is only true when pollen is compared with micro-charcoal where charcoal dispersion zones are well known. To assume that anthropogenically-introduced charcoal comes from the cave locale is to implicitly assume the Principle of Least Effort. If Neanderthals foraged as far as the Inuit for their woods, they would cover much of the pollen catchment area and balance the scales much more. Even if they gathered fuelwood locally, provided that they foraged generally over wider areas, this foraging area (of similar magnitude to pollen catchment zones) would represent *potential* wood foraging areas, and this representation is seen in the pollen. The different biases are likewise addressed in this and following chapters. The only remaining criticism is that charcoal represents single events, whereas pollen likely represents more continuous input into sediments over time, and differences could arise from that alone if vegetation changed. This difference is valid if we only consider single burning events; however, most studied charcoal is taken from sedimentary palimpsests, mixing different fire events and more closely resembling pollen input.

I calculated discrepancies between charcoal and pollen records using this equation:

Discrepancy(A) = %(CharcoalA) - %(PollenA)

Values of 0 meant that fuelwood use and pollen (landscape) prevalence was identical, suggesting no selection. Positive values means selection towards a fuelwood and gathering it in higher proportions than random landscape gathering. Negative values means an avoidance of it, despite it being available. 100 would indicate that there is only one fuelwood and it is not apparently present anywhere in the pollen record, and -100 would be where only one arboreal species is present in the pollen record, and it is entirely absent from the charcoal.

If genera are found as charcoal but not pollen, they were certainly burnt, and potentially brought long distances. If genera are found as pollen but not charcoal, they were locally available but not burnt (or burnt in negligible quantities, leaving no charcoal). Sometimes pollen and/or charcoal values for a single genus are means of several values, where the authors provided multiple pollen samples from different areas of the site in the same level, or from different individual hearth features in the same level. In these instances, I use Welch's (two-sample) T-test (p = 0.05 threshold) to determine whether differences between charcoal and pollen means are statistically significant.

where t = the ratio of difference between the means of the two samples, ratioed to the combined standard deviations of the two samples. Welch's test assumes that each sample is normally-distributed, ascribing finite probabilities for negative parameter values. This does not work when the quantities are percentages; I addressed this issue by assuming the distributions are log-normally distributed (as is good practice with all pollen data - Yamamoto et al. 2015), putting the data's logarithm into the test. However, for genera scoring 0, log(0) is undefined – I replaced this by the maximum value which could have been present but undetected in each record; this is 0.05%, hence log(0.05) was used in lieu of log(0).

From this study, 25 genera were found in Iberian Palaeolithic environments around these caves (not all genera were present at every cave): *Acer, Alnus, Arbutus, Betula, Buxus, Castanea, Corylus, Erica, Fraxinus, Hippophae, Ilex, Juniperus, Olea, Phillyrea, Pinus, Pistacia, Prunus, Quercus, Rhamnus, Salix, Sorbus, Tamarix, Taxus, Ulmus* and *Viburnum.* Of these, only 12 genera were used as fuel, viz *Acer, Betula, Erica, Fraxinus, Hippophae, Juniperus, Olea, Pinus, Prunus, Quercus, Salix* and *Sorbus. Pinus* dominated the fuel record, appearing to be preferred Neanderthal fuelwoods. Overwhelming use of pine corresponds with other Neanderthal sites (see Chapter Eight, p.237). The following Tables, 5.2 to 5.11, taken verbatim from my previous work (Knight unpubl.) show the raw data from the Iberian sites. All other work in this chapter is new material. Those which contain two-tailed P values and significance tests are where means had been created from multiple charcoal *and* multiple pollen samples, and two sets of means could be compared. Where these P values are absent, statistical comparison of two datasets where means had been taken, could not be undertaken.

IV.II: Results.

Tables 5.2-5.11: Comparing charcoal and pollen records in Middle Palaeolithic sites; in order, El Esquilleu, Cova de Coll Verdaguer, Cueva del Camino, Gorham's Cave and Abric Romani.

5.2: El Esquilleu Level IX-XIII

Genus	**Charcoal %**	**Pollen %**	**Discrepancy**	**Two-tailed P value**	**Statistically significant?**
Alnus	0.00	5.40	5.40 (P)	0.42	No
Betula	9.62	13.32	3.70 (P)	0.25	No
Corylus	0.00	12.76	12.76 (P)	0.19	No
Pinus	41.42	54.91	13.49 (P)	0.65	No
Quercus	0.00	0.00	0.00	*	*
Salix	0.00	0.00	0.00	*	*
Sorbus	48.96	0.00	48.96 (C)	0.0475	Yes
Ulmus	0.00	13.60	13.60 (P)	0.18	No

8.03% excluded from arboreal charcoal (Unidentified Deciduous).

5.3: El Esquilleu Level XIV-XIX

Genus	**Charcoal %**	**Pollen %**	**Discrepancy**	**Two-tailed P value**	**Statistically significant?**
Alnus	0.00	0.00	0.00	*	*
Betula	1.54	20.44	18.90 (P)	0.95	No
Corylus	0.00	0.00	0.00	*	*
Pinus	96.32	51.50	44.82 (C)	0.36	No
Quercus	0.00	0.00	0.00	*	*
Salix	0.00	0.00	0.00	*	*
Sorbus	2.14	0.00	2.14 (C)	0.18	No
Ulmus	0.00	28.07	28.07 (P)	0.19	No

3.16% excluded from arboreal charcoal (Unidentified Deciduous).

5.4: El Esquilleu Level XX-XXX

Genus	**Charcoal %**	**Pollen %**	**Discrepancy**	**Two-tailed P value**	**Statistically significant?**
Alnus	0.00	4.66	4.66 (P)	0.37	No
Betula	2.38	16.11	13.73 (P)	0.98	No
Corylus	0.00	0.00	0.00	*	*
Pinus	97.62	46.10	51.52 (C)	0.13	No
Quercus	0.00	8.00	8.00 (P)	0.37	No
Salix	0.00	8.11	8.11 (P)	0.37	No
Sorbus	0.00	0.00	0.00	*	*
Ulmus	0.00	17.02	17.02 (P)	0.37	No

2.68% excluded from arboreal charcoal (Unidentified Deciduous).

5.5: Cova de Coll Verdaguer Unit I			
Genus	**Charcoal %**	**Pollen %**	**Discrepancy**
Acer	0.00	0.00	0.00
Alnus	0.00	0.00	0.00
Betula	0.00	1.38	1.38 (P)
Buxus	0.00	0.69	0.69 (P)
Juniperus	0.00	1.38	1.38 (P)
Olea	0.00	0.69	0.69 (P)
Pinus	87.10	93.78	6.68 (P)
Prunus	11.91	1.38	10.53 (C)
Quercus (deciduous)	0.99	0.69	0.30 (C)

6.06% excluded from arboreal charcoal (*Conifer, Angiosperm, Ephedra*).

5.6: Cova de Coll Verdaguer Unit II			
Genus	**Charcoal %**	**Pollen %**	**Discrepancy**
Acer	0.00	0.39	0.39 (P)
Alnus	0.00	0.93	0.93 (P)
Betula	0.00	0.39	0.39 (P)
Buxus	0.00	0.47	0.47 (P)
Juniperus	0.00	3.47	3.47 (P)
Olea	0.00	0.78	0.78 (P)
Pinus	94.80	91.18	3.62 (C)
Prunus	5.20	0.77	4.43 (C)
Quercus (deciduous)	0.00	1.62	1.62 (P)

7.06% excluded from arboreal charcoal (*Conifer, Angiosperm, Ephedra*).

5.7: Cueva del Camino Level V			
Genus	**Charcoal %**	**Pollen %**	**Discrepancy**
Alnus	0.00	19.92	19.92 (P)
Betula	6.91	1.29	5.62 (C)
Corylus	0.00	14.49	14.49 (P)
Fraxinus	0.40	0.00	0.40 (C)
Olea	0.00	2.47	2.47 (P)
Pinus	91.87	51.30	40.57 (C)
Quercus	0.40	4.60	4.20 (P)
Salix-Populus	0.40	0.93	0.53 (P)
Ulmus	0.00	5.00	5.00 (P)

1.20% excluded from arboreal charcoal (*Maloideae*).

5.8: Gorham's Cave Level IV					
Genus	**Charcoal %**	**Stratigraphic Pollen %**	**Discrepancy (charcoal with stratigraphic)**	**Coprolite Pollen**	**Discrepancy (charcoal with coprolite)**
Acer	0.00	0.00	0.00	3.54	3.54 (P)
Alnus	0.00	0.00	0.00	2.08	2.08 (P)
Arbutus	0.00	3.04	3.04 (P)	1.46	1.46 (P)
Betula	0.00	1.53	1.53 (P)	1.21	1.21 (P)
Castanea	0.00	0.00	0.00	1.12	1.12 (P)
Corylus	0.00	1.11	1.11 (P)	2.77	2.77 (P)
Erica	1.65	0.00	1.65 (C)	0.00	1.65 (C)
Fraxinus	0.00	2.53	2.53 (P)	2.78	2.78 (P)
Ilex	0.00	12.17	12.17 (P)	3.20	3.20 (P)
Juniperus	1.65	38.93	37.28 (P)	13.51	11.86 (P)
Olea	2.48	3.86	1.38 (P)	2.06	0.42 (C)
Phillyrea	0.00	0.00	0.00	2.65	2.65 (P)
Pinus	94.18	25.20	68.98 (C)	26.02	68.16 (C)
Pistacia	0.00	7.92	7.92 (P)	2.65	2.65 (P)
Prunus	0.00	0.00	0.00	0.39	0.39 (P)
Quercus	0.00	1.05	1.05 (P)	19.91	19.91 (P)
Rhamnus	0.00	0.00	0.00	3.69	3.69 (P)
Salix	0.00	2.67	2.67 (P)	3.68	3.68 (P)
Tamarix	0.00	0.00	0.00	1.56	1.56 (P)
Taxus	0.00	0.00	0.00	3.48	3.48 (P)
Ulmus	0.00	0.00	0.00	1.97	1.97 (P)
Viburnum	0.00	0.00	0.00	0.27	0.27 (P)

5.61% excluded from arboreal charcoal (*Rosaceae/Pomoideae, Cistaceae, Fabaceae, Lonicera*).

5.9: Abric Romani Zone V			
Genus	**Charcoal %**	**Pollen %**	**Discrepancy**
Acer	1.81	0.00	1.81 (C)
Hippophae	0.46	0.00	0.46 (C)
Juniperus	0.00	7.25	7.25 (P)
Olea	0.46	0.00	0.46 (C)
Pinus	96.82	74.15	22.67 (C)
Prunus	0.00	0.00	0.00
Quercus (deciduous)	0.46	8.63	8.17 (P)
Rhamnus	0.00	9.96	9.96 (P)
Salix	0.00	0.00	0.00

4.75% excluded from arboreal pollen (Mesic trees), 3.51% excluded from arboreal charcoal (*Hedera, Vitis*).

5.10: Abric Romani Zone IV

Genus	**Charcoal %**	**Pollen %**	**Discrepancy**	**Two-tailed P value**	**Statistically significant?**
Acer	0.00	0.00	0.00	*	*
Hippophae	0.00	0.00	0.00	*	*
Juniperus	0.00	6.85	6.85 (P)	0.013	Yes
Olea	0.00	0.00	0.00	*	*
Pinus	99.95	91.92	8.03 (C)	0.057	No
Prunus	0.00	0.00	0.00	*	*
Quercus (deciduous)	0.00	1.22	1.22 (P)	0.016	Yes
Rhamnus	0.00	0.00	0.00	*	*
Salix	0.05	0.00	0.05 (C)	0.42	No

5.11: Abric Romani Zone III

Genus	**Charcoal %**	**Pollen %**	**Discrepancy**	**Two-tailed P value**	**Statistically significant?**
Acer	0.00	0.00	0.00	*	*
Hippophae	0.00	0.00	0.00	*	*
Juniperus	0.00	5.19	5.19 (P)	0.002	Yes
Olea	0.00	1.39	1.39 (P)	0.000068	Yes
Pinus	99.87	70.38	29.49 (C)	0.016	Yes
Prunus	0.13	0.00	0.13 (C)	0.39	No
Quercus (deciduous)	0.00	5.57	5.57 (P)	0.000074	Yes
Rhamnus	0.00	17.47	17.47 (P)	0.002	Yes
Salix	0.00	0.00	0.00	*	*

2.51% excluded from arboreal pollen (Mesic trees).

* = cannot perform Welch’s T-test on this data.

Table 5.12: Discrepancies between charcoal and pollen records for 25 genera in Middle Palaeolithic Iberia. The methodology for calculating this %charcoal - %pollen value is outlined on p.144.

Overall Averages		
Genus	**No. of Layers found as pollen, charcoal or both**	**Average % charcoal minus % pollen**
Acer	6	0.24
Alnus	7	-4.42
Arbutus	1	-3.04
Betula	7	-4.86
Buxus	2	-0.58
Castanea	1	0.00
Corylus	5	-5.67
Erica	1	1.65
Fraxinus	2	-1.07
Hippophae	3	0.15
Ilex	1	-12.17
Juniperus	6	-10.24
Olea	7	-0.89
Phillyrea	1	0.00
Pinus	10	24.95
Pistacia	1	-7.92
Prunus	6	2.52
Quercus	10	-2.95
Rhamnus	4	-6.86
Salix (Salix-Populus)	8	-1.41
Sorbus	3	17.03
Tamarix	1	0.00
Taxus	1	0.00
Ulmus	5	-12.74
Viburnum	1	0.00

Table 5.13: Identification of genera as fuelwoods or not in Middle Palaeolithic Iberia.

Other Genera	**Rare Fuelwood Genera (only 1 example)**	**Occasional Fuelwood Genera (2-3 examples)**	**Common Fuelwood Genera (4+ examples)**
Alnus, Arbutus, Buxus, Castanea, Corylus, Ilex, Phillyrea, Pistacia, Rhamnus, Tamarix, Taxus, Ulmus, Viburnum	*Acer, Erica, Fraxinus, Hippophae, Juniperus, Populus*	*Olea, Prunus, Quercus, Salix, Sorbus*	*Betula, Pinus*

Within these levels, only *Quercus* and *Pinus* were found as pollen at every site. The rarest genera, only occurring as pollen in one level, are *Arbutus, Castanea, Erica, Ilex, Phillyrea, Pistacia, Tamarix, Taxus* and *Viburnum*. Of these latter rare genera, only *Erica* was burnt (and this genus could have been used as bedding and subsequently burnt in clearance rather than as fuel), suggesting that infrequently-encountered woods were rarely perceived as fuel by Neanderthals primarily because of their scarcity rather than necessarily because of their attributes. Five rarer genera (*Castanea, Phillyrea, Tamarix, Taxus, Viburnum*) are only found in hyena coprolites in Gorham's Cave rather than as sedimentary pollen. This indicates that they may not have been found locally, in contrast to airborne pollen. Given that hyenas and Neanderthals never concurrently inhabited the same cave (although possibly interseasonally within the same year), Neanderthals may not have encountered these woods at all locally. *Erica, Hippophae* and *Sorbus* on the other hand, are found as charcoal but not as pollen, suggesting intentional transport over longer distances.

Thus from the pollen record, Iberian Neanderthals may have been familiar with these genera in decreasing proportions: *Pinus/Quercus, Salix, Alnus/Betula/Olea, Acer/Juniperus/Prunus, Corylus/Ulmus, Rhamnus, Hippophae/Sorbus, Buxus/Fraxinus, Arbutus/Erica/Ilex/Pistacia*. Importantly, this listing is unequally spaced, with higher numbers of pine and oak than anything else, and *Rhamnus*-downwards only occurring infrequently. If Neanderthals did not select for fuel, *Pinus/Quercus* fuels would be found at most sites, and *Arbutus/Erica/Pistacia* at fewest (not taking the proportion of charcoal for each genus into account either).

However, this is distinctly not the case; *Pinus* was burnt at every site, dominating every record except for Gorham's Cave, whilst *Quercus* was only burnt at three, although present in every environment. *Betula* was also common, though in low quantities. *Sorbus* was strongly selected towards in El Esquilleu, being burnt at high levels (48% of all charcoal in Levels IX-XIII) without any pollen presence, suggesting longer-distance transport. Neanderthals not only *burnt* pine at high levels, but most importantly *selected* towards it - charcoal percentages being much higher than pollen percentages. Pine is environmentally common through MIS 3 Neanderthal sites (Vidal-Matutano et al. 2015, Uzquiano 2008) – Neanderthals may have selected it initially because of ubiquity, and subsequently for burning qualities. As outlined more fully in Chapter Nine (p.248), pine would be easy to gather, having a low bending strength of 43.5MPa and a low density of 0.47g/cm^3, and would burn well with a high calorific value of 18kJ/g.

V: Pollen Recalibrations.

Before this thesis discusses the motivations behind these apparent preferences towards certain fuelwood types, and avoidance of others, it is crucial to ensure that these apparent discrepancies were actually present in Neanderthal fire regimes, and not artefacts of taphonomic bias. These two records are formed not only of two wholly different types of material, but each site is also subject to unique environments, burning regimes and post-depositional histories. Uniform patterns of discrepancy across multiple sites (the same fuel genera selected for and the same ones rejected) does not prove intentionality, as this could result either from cultural practices (identical Neanderthal fuel selection) or taphonomic factors (identical genera-specific differential destruction of different charcoals/pollens).

Although discussed further in Chapter Six (p.164), differential charcoal production and destruction can confuse anthracological records. More charcoal can theoretically be produced at lower temperatures, from denser woods with lower ash contents and higher resin contents (Alvarez-Alvarez et al. 2018, Rossen and Ohlson 1985, Terral 1996), which are all theoretically fuelwood-genera-dependent. Likewise, charcoal fragments at different rates according to production temperature, tree age, density, moisture, resin and ray-cell contents (Assis et al. 2016, Braadbaart and Poole 2008). These metrics are frequently standardizable across a genus, and easily testable here, given that the greatest variable, the transportation mechanism, is anthropogenically-determined and the thesis' focus. The following chapters address these issues by creating new data from experimental sources.

Pollen is however more complicated, its reliability depending on multiple factors. Whilst charcoal is anthropogenically-introduced into the sediment, pollen is naturally introduced in three main ways; wind (anemophilous), insects (entomophilous) or both (ambophilous). Smaller amounts also enter via water (hydrophilous) or vertebrates (zoophilous) as well as on the fuelwoods themselves. Differential lossese from each of these sources is severely under-studied, and as Pearsall (2000) quotes, "prehistoric pollen proportions should be taken as rough estimates of past tree distributions, and are not an exact representation of prehistoric forest composition, due to variations in dispersal rates between tree species". Another unknown variable is subsequent differential loss once within sediments, although higher sporopollenin in pollen exines increases resistance to oxidation and microbial attack

(Grienenberger and Quilichini 2021, Jardine et al. 2015, McGarry and Caseldine 2004). Further differential loss may also relate to the chemicals used in different scientific preparation techniques: sodium hexametaphospate, bleach, HCl, HF, KOH, sodium polytungstate, acetic anhydride and ZnCl2 (Kovacik and Cummings 2018, Ma et al. 2016). This represents much more variability than within charcoal preparation techniques, introducing artificial study-specific (and site-specific) biases.

V.I: Methodology.

Whilst most variables of differential pollen bias are currently unstudied and beyond the scope of this thesis, many modern papers study differential pollen *productivity.* I therefore compiled and recalibrated data from these studies, gathered from internet and library studies utilizing keywords in English, French, Italian, Spanish and German. The results used means of various studies' pollen productivities values ratioed to a *Pinus = 1* value. This was used as *Pinus* is the most common genus in Middle Palaeolithic charcoal and pollen records, and is included in virtually all studies as a reference point (for those studies not including *Pinus*, I used *Quercus = 1* as a reference point instead, ratioed to *Quercus = 1.36,* which is *Quercus'* mean productivity ratioed to *Pinus = 1*). This value is an average; different species of pine may have different pollen production, or vary under different conditions (time of day, wind speed and direction, season, air moisture etc.) making inter-study comparison difficult. Naturally, some genera present more datapoints than others, from being better studied, and these genera produce more reliable ratios. However, less-reliable genera are less-studied precisely because they are less common, and as this also applies in the Middle Palaeolithic, the occasional low number of datapoints does not adversely affect this study. Where multiple proportions to *Pinus* were given, from the same or different studies, I created mean proportions.

V.II: Differential Pollen Production Results.

Table 5.14: Pollen productivity for 23 genera, in proportion to pine, counted by number of grains. Each pollen productivity value corresponds to a different study.

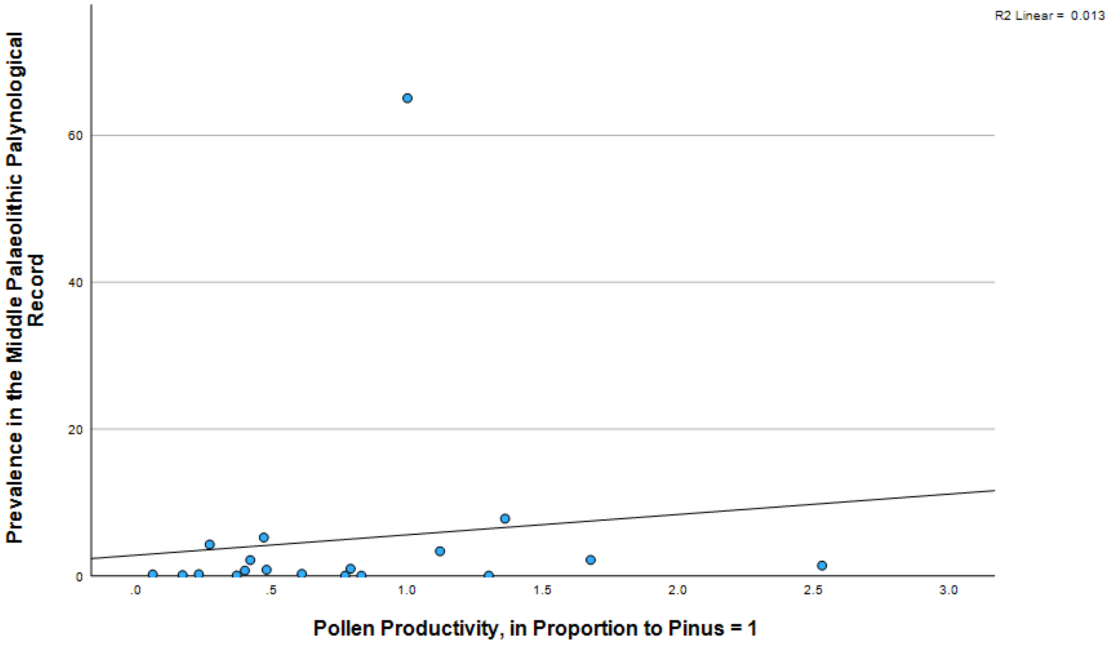
Genus	**Pollen Productivities in proportion to *Pinus* = 1**	**Mean Pollen Productivity in proportion to *Pinus* = 1**
Phillyrea	0.06	0.06
Pistacia	0.09	0.09
Larix	0.10	0.10
Sambucus	0.12, 0.21	0.17
Buxus	0.23	0.23
Ulmus	0.20, 0.20, 0.22, 0.45	0.27
Juglans	0.11, 0.62	0.37
Castanea	0.40	0.40
Picea/Larix	N/A	0.41
Corylus	0.10, 0.14, 0.25, 0.31, 0.35, 1.37	0.42
Juniperus	0.32, 0.37, 0.73	0.47
Fraxinus	0.12, 0.16, 0.16, 0.18, 0.24, 0.25, 0.27, 0.74, 2.24	0.48
Populus	0.22, 0.31, 1.31	0.61
Picea	0.15, 0.28, 0.30, 0.31, 0.33, 0.4, 0.93, 1.08, 2.66	0.72
Acer	0.02, 0.03, 0.13, 0.22, 3.45	0.77
Salix	0.02, 0.04, 0.19, 0.22, 0.24, 0.28, 0.46, 4.87	0.79
Carpinus	0.28, 0.45, 0.47, 0.56, 2.41	0.83
Pinus	N/A	1.00
Betula	0.36, 0.45, 0.55, 0.58, 0.63, 0.81, 1.28, 1.44, 1.57, 1.62, 1.70, 2.39	1.12
Fagus	0.22, 0.54, 1.03, 1.18, 1.79, 3.06	1.30
Quercus	0.22, 0.29, 0.32, 0.38, 0.91, 1.33, 1.46, 5.93	1.36
Alnus	0.31, 0.74, 0.78, 1.42, 2.03, 2.54, 2.74, 2.75	1.676
Olea	2.53	2.53

Abraham and Kozakova (2012), Baker et al. (2016), Bunting et al. (2005), Brodstrom et al. (2004), Gaillard et al. (2021), Li et al. (2015), Matthias et al. (2012), Mazier et al. (2008, 2012), Molina et al. (1996), Nielsen (2004), Poska et al. (2011), Rasanen et al. (2007), Soepboer et al. (2007), von Stedingk et al. (2008), Sugita et al. (1999, 2009), Theuerkauf et al. (2013), Twiddle et al. (2012), Wieczorek and Herzschuh (2020).

Table 5.15: An original table showing the abundance of 32 genera in the Iberian Middle Palaeolithic pollen record from the analysed sites.

Genus.	**Number of Instances.**	**Proportion within sites containing pollen of this Genus.**	**Proportion within all Neanderthal sites where I have analysed pollen and charcoal records.**
Carpinus	1	0.29	0.02
Fagus	1	0.29	0.02
Myrica	1	0.23	0.02
Taxus	1	0.36	0.02
Vitis	1	0.29	0.02
Acer	1	0.39	0.03
Viburnum	1	0.29	0.04
Juglans	2	0.35	0.05
Abies	1	0.88	0.06
Sambucus	3	0.49	0.10
Ostrya	1	1.75	0.12
Prunus	2	1.08	0.14
Myrtus	1	1.30	0.17
Phillyrea	2	1.43	0.19
Buxus	3	1.10	0.22
Arbutus	2	1.87	0.25
Populus	2	2.02	0.27
Erica	2	4.55	0.61
Pistacia	3	3.17	0.63
Castanea	3	3.61	0.72
Ilex	1	12.17	0.81
Fraxinus	4	3.12	0.83
Salix	5	2.90	0.97
Olea	9	2.33	1.40
Rhamnus	5	5.77	1.92
Corylus	6	5.36	2.15
Alnus	6	5.42	2.17
Betula	9	5.59	3.35
Ulmus	5	12.80	4.27
Juniperus	9	8.72	5.23
Quercus	13	8.99	7.79
Pinus	15	65.05	65.05

The Neanderthal palynological record contains no hydrophilous (water-pollinated) or zoophilous (vertebrate-pollinated) genera, as expected given that both water streams and animals seldom enter cave sites (while Neanderthals are present, except potentially as dead prey species). The remaining genera are mostly anemophilous (wind-pollinated: *Abies, Alnus, Betula, Carpinus, Corylus, Fagus, Fraxinus, Juglans, Juniperus, Myrica, Phillyrea, Pinus, Pistacia, Populus, Quercus, Taxus, Ulmus, Vitis*), with some being entomophilous (insect pollinated: *Arbutus, Arctostaphylos, Buxus, Castanea, Erica, Ilex, Myrtus, Prunus, Sambucus, Viburnum)* or ambophilous (pollinated from multiple sources: *Acer, Olea, Ostrya, Rhamnus, Salix*). I have not reviewed pollen productivities of all of these genera, looking at 16 anemophilous, 3 entomophilous and 3 ambophilous genera. The lack of data on insect-pollinated genera can skew this data. Different genera produce different sizes of pollen (although it does not vary within species within the same genus – Doaigey et al. 2018), and there is some evidence that pollinators prefer genera with smaller pollen diameters (Hao et al. 2020). However, overall correlations between pollen diameter and pollen abundance and spread are currently under-studied.



Graph 5.1: A graph comparing Tables 4.13 and 4.14, proving that apparent Middle Palaeolithic arboreal landscapes were not an artefact of differential pollen production (R2 = 0.013).

However, wind-pollinated plants produce more pollen than insect-pollinated ones, relative to *Pinus* = 1 (0.6978 compared to 0.2667). This trend is fully expected, given that wind is a much less certain and direct pollinator than insects, and consequently more pollen will be lost, in theory in cave sediments. Ambophilous genera appear to produce vastly more pollen (1.3633) which is unexpected; this however is driven by the very high pollen value of 2.53 for *Olea*; if this is excluded, the values become 0.78, much more comparable to wind-pollinated plants.

I find that wind-pollinated genera are potentially overrepresented in palynology, and certain genera *do* produce more pollen than others, correlating with modern ecological findings of Elenga et al. (2000) and Lebamba et al. (2009). However, how does this translate to Middle Palaeolithic anthracological records? Comparing pollen production prevalence with actual occurrences of various genera in Neanderthal palynological records, we find no correlations (Graph 5.1, above). This suggests that *apparently* prevalent tree types (as seen palynologically) were *actually* abundant in Middle Palaeolithic landscapes, and that these apparent abundances were not artefacts of differential pollen productivity by genus. As aforementioned, wind pollination is highly variable and depends on prevailing wind direction, carrying pollen much further than insect pollinators. Furthermore, insect pollinators would not specifically travel to caves unless to burrow into loose exposed sediments, which further confuses matters (as in Shanidar with burrowing bees – Hunt et al. 2023). Furthermore, insects may preferentially choose certain genus' flowers over others, and this of course varies from pollinator to pollinator, so the often-unknown pollinator species using each cave site affects a sample's representativeness, although suitable pollinators must have been *present* for all insect-pollinated genera to survive. Of the 27 genera found in both anthracological and palynological diagrams in Middle Palaeolithic sites, 19 are partially or wholly anemophilous. This helps ensure that most Middle Palaeolithic pollen was not collected by potentially chronologically-unreliable burrowing pollinators but instead collected as random landscape samples. Each pollination category is not equally common in the Middle Palaeolithic record: entomophilous genera only form 10.53% (found in 65 examples) of the charcoal, with most being anemophilous (74.74%, in 236 examples). When compared to the complementary pollen, similar patterns emerge, with confirmed entomophilous genera only providing 3.06% of the pollen (18 examples), compared to 92.12% (and 81 examples) of anemophilous genera. Admittedly the dominance of *Pinus,* an anemophilous genus, contributes to these numbers, but even without this the difference is notable. This suggests that Neanderthals burnt predominantly wind-pollinated plants and that these were most environmentally-abundant.

V.III: Recalibration Tables.

When the Neanderthal palynological diagrams which are compared to chronologically-correlating anthracological diagrams are recalibrated to take pollen production bias into account and show the original proportions of arboreal genera (excepting Abric Romani Zone III, which has too high a proportion of unratioed *Prunus* pollen), several patterns emerge (see Tables 5.16-5.21 below). Compared to original uncalibrated sets, most recalibrated sets show either similar or increased charcoal-pollen variation. A total discrepancy of 0 between these two sets would suggest no anthropogenic selection (if *Quercus* formed 5% of charcoal, it would also form 5% of pollen), and a total discrepancy of 100 would show a genus is only present as either the sole fuel with no apparent landscape signature, or present as the only nearby tree but not burnt at all. The fact that these discrepancy values *increase* when recalibrated suggests that differential pollen *production* does not cause the differences between a genus' charcoal and pollen presence, although the effects of differential pollen *destruction* is unknown. Therefore other factors must be responsible; currently-unquantifiable pollen destruction, charcoal-related biases (see Chapter Six) or active Neanderthal fuel choice.

Table 5.16-5.21: Recalibrating charcoal-pollen discrepancies to account for pollen production bias in Middle Palaeolithic Iberian sites, viz. El Esquilleu, Cueva del Camino and Abric Romani. A (P) means that the discrepancy (where 0 is charcoal and pollen in exactly equal proportions, and 100 is a genus exclusively found as either pollen OR charcoal, but not at all as the other) is towards pollen (this genus has a higher pollen % (out of 100% arboreal coverage) than charcoal %). A (C) means that the discrepancy is towards charcoal.

5.16: El Esquilleu Level IX-XIII		
Genus	Original Charcoal-Pollen Discrepancy	Charcoal-Pollen Discrepancy (original charcoal, recalibrated pollen)
Alnus	5.40 (P)	2.14 (P)
Betula	3.70 (P)	1.73 (C)
Corylus	12.76 (P)	20.15 (P)
Pinus	13.49 (P)	5 (C)
Sorbus	48.96 (C)	48.96 (C)
Ulmus	13.60 (P)	33.41 (P)
Total Discrepancy	**48.96**	**55.7**

5.17: El Esquilleu Level XIV-XIX		
Genus	Original Charcoal-Pollen Discrepancy	Charcoal-Pollen Discrepancy (original charcoal, recalibrated pollen)
Betula	18.90 (P)	8.97 (P)
Pinus	44.82 (C)	66.67 (C)
Sorbus	2.14 (C)	2.14 (C)
Ulmus	28.07 (P)	59.85 (P)
Total Discrepancy	**46.96**	**68.82**

5.18: El Esquilleu Level XX-XXX		
Genus	Original Charcoal-Pollen Discrepancy	Charcoal-Pollen Discrepancy (original charcoal, recalibrated pollen)
Alnus	4.66 (P)	1.95 (P)
Betula	13.73 (P)	7.72 (P)
Pinus	51.52 (C)	65.26 (C)
Quercus (deciduous)	8.00 (P)	4.13 (P)
Salix	8.11 (P)	7.21 (P)
Ulmus	17.02 (P)	44.25 (P)
Total Discrepancy	**51.52**	**65.26**

5.19: Cueva del Camino Level V		
Genus	Original Charcoal-Pollen Discrepancy	Charcoal-Pollen Discrepancy (original charcoal, recalibrated pollen)
Alnus	19.92 (P)	9.67 (P)
Betula	5.62 (C)	5.97 (C)
Corylus	14.49 (P)	28.07 (P)
Fraxinus	0.40 (C)	0.40 (C)
Olea	2.47 (P)	0.79 (P)
Pinus	40.57 (C)	50.13 (C)
Quercus (deciduous)	4.20 (P)	2.35 (P)
Salix-Populus	0.53 (P)	0.56 (P)
Ulmus	5.00 (P)	15.07 (P)
Total Discrepancy	**46.59**	**56.51**

5.20: Abric Romani Zone V

Genus	Original Charcoal-Pollen Discrepancy	Charcoal-Pollen Discrepancy (original charcoal, recalibrated pollen)
Acer	1.81 (C)	1.81 (C)
Hippophae	0.46 (C)	0.46 (C)
Juniperus	7.25 (P)	14.19 (P)
Olea	0.46 (C)	0.46 (C)
Pinus	22.67 (C)	28.60 (C)
Quercus (deciduous)	8.17 (P)	5.38 (P)
Rhamnus	9.96 (P)	11.75 (P)
Total Discrepancy	**25.38**	**31.33**

Rhamnus pollen proportion = 0.78 (ambophilous average, excluding *Olea*).

5.21: Abric Romani Zone IV

Genus	Original Charcoal-Pollen Discrepancy	Charcoal-Pollen Discrepancy (original charcoal, recalibrated pollen)
Juniperus	6.85 (P)	13.57 (P)
Pinus	8.03 (C)	14.36 (C)
Quercus (deciduous)	1.22 (P)	0.84 (P)
Salix	0.05 (C)	0.05 (C)
Total Discrepancy	**8.08**	**14.41**

Pinus, the previously highest-selected fuel, becomes even more favoured when differential pollen production is considered, as it is a high pollen producer. *Corylus* and *Ulmus* become much more selected against, as expected given both are harder to burn (see Chapter Nine). *Quercus*, which was surprisingly selected against given it is a highly-regarded fuel, becomes slightly more selected for (although still selected against compared to environmental availability). These results suggest that apparent surprises in Neanderthal fuel choice, from an optimization standpoint, may be partially explained by confusion introduced by differential pollen production. Table 5.22 below shows the changed discrepancies, also shown on Graph A30 in Appendix Seven. Overall, the average charcoal-pollen discrepancy changes from 37.92 to 48.67; the exact opposite of that expected if pollen production biases caused the discrepancy. It seems instead that, coincidentally, pollen production biases partially mask discrepancies.

Table 5.22: Changing charcoal-pollen discrepancies for 10 genera following pollen production bias recalibration. This is also shown on Graph A30 in Appendix Seven.

Genera	Original Discrepancies	Average Original Discrepancy	Recalibrated Discrepancy	Average Recalibrated Discrepancy
Alnus	-19.92, -5.4, -4.66	9.99 (P)	-9.67, -2.14, -1.95	4.59 (P)
Betula	-18.9, -13.73, -3.7, 5.62	7.68 (P)	-8.97, -7.72, 1.7, 5.97	2.26 (P)
Corylus	-14.49, -12.76	13.63 (P)	-28.07, -20.15	24.11 (P)
Juniperus	-7.25, -6.85	7.05 (P)	-14.19, -13.57	13.88 (P)
Olea	-2.47, 0.46	1.01 (P)	-0.79, 0.46	0.17 (P)
Pinus	-13.49, 8.03, 22.67, 40.57, 44.82, 51.52	25.69 (C)	5, 14.36, 28.6, 50.13, 65.26, 66.67	38.34 (C)
Quercus (deciduous)	-8.17, -8, -4.20, -1.22	5.40 (P)	-5.38, -4.13, -2.35, -0.84	3.18 (P)
Rhamnus	-9.96	9.96 (P)	-11.75	11.75 (P)
Salix *(Salix-Populus)*	-8.11, -0.53, 0.05	2.86 (P)	-7.21, -0.56, 0.05	2.57 (P)
Ulmus	-28.07, -17.02, -13.6, -5	15.92 (P)	-59.85, -44.25, -33.41, -15.07	38.15 (P)

VI: Conclusion.

This chapter has discussed the nature of fuelwoods and the motivations behind fuel choice and its implications. Looking at potential Neanderthal fuels, whilst instances of burning bone, coal and dung are present, wood was by far the predominant fuel. I have introduced the Principle of Least Effort, and examined it through modern ethnographic analogies. If Neanderthals did not follow the Principle of Least Effort, active thought may have gone into their fuel procurement. Comparing Middle Palaeolithic fuelwood records (charcoal) with local environments (pollen), I noted several discrepancies which cannot readily be explained in terms of differential pollen production. The inference thus far is that these discrepancies could represent active Neanderthal fuelwood choice, either from fire-optimization or foraging-optimization principles. The following two chapters discuss the effects of recalibrating charcoal production and fragmentation on these discrepancies, and whether such discrepancies are only artefacts of these taphonomic processes.

Chapter Six: Methodology.

The results from the last chapter suggest that Active Selection could have been important for Neanderthal hunter-gatherers; if charcoal and pollen compared are reliable, unbiased records. However, each record has its own concerns. In the last chapter I examined whether differential pollen production, transportation and destruction causes artificial genera-specific biases. Differential pollen production alone, the only element which has been sufficiently researched, did not cause the discrepancies seen here. If anthracology was a wholly unbiased preservation mechanism, direct anthropogenic choice must have caused these discrepancies. Charcoal does however suffer from similar biases, which form two main categories:

1) Differential charcoal production, caused by either genera-specific wood traits or carbonization temperature.
2) Differential charcoal fragmentation, resulting from innate morphological differences in charcoals (due to taxa differences or carbonization temperature), different taphonomic conditions or different recovery techniques. This is particularly important if the results are interpreted as number of fragments for each genus.

These issues are well studied, but sufficiently standardized information for many genera has not yet been created. I therefore address this with two experiments, one for each issue.

I: Conversion Rate.

Different woody taxa vary significantly in calorific value and density (Marston 2009, Wright et al. 2015), and certain genera have higher ash contents than others (Henry et al. 2020). Ash represents a wood's incombustible fraction (Braadbaart et al. 2012, Terral 1996), or alternatively the remains of complete as opposed to incomplete combustion (Thery-Parisot et al. 2010). If ash contents vary between genera (Esteves et al. 2023, Terral 1996), and ash is incombustible, then more ash recovered means (a) lower calorific values for the wood and (b) less combustible/potentially charcoalifiable matter. Braadbaart et al.'s (2012) theory is plausible, as ash contains many incombustible elements and compounds rarely found in charcoal (Ca, Mg, K etc.), suggesting an incombustible byproduct. If woods vary in ash content, they could also vary in charcoal content. However, many other factors are at play.

Wood density and size is important. Charcoal results from incomplete combustion in anaerobic environments; limiting oxygen theoretically increases charcoal yields. Dense woods such as *Fagus* (Knapp et al. 2013) have less internal oxygen than less-compact woods, and thus produce more charcoal (Gomes et al. 2014, Rossen and Ohlson 1985). However, most oxygen naturally comes from outside burning branches, and in fact the reverse has also been observed, where softwoods create more charcoal than dense ones (Loreau 1994). Certain coniferous softwoods are also extremely resinous. This flammable substance complicates matters by both theoretically using up oxygen whilst burning itself, and also filling interstices with resin rather than air. Size also matters; smaller-diameter twigs often completely combust, whereas larger logs externally combust but only char in the centre where oxygen is excluded. However, whilst *tree* size varies by taxa, *fuel* size differences depend on a tree's age, climatic growth conditions, fuel transport logistics, and selection of living wood or deadwood. Thus this difference is not taxa-specific. The exception is where taxa (e.g. *Pinus*) shed small branches frequently (Thery-Parisot et al. 2018); burnt thus, such taxa theoretically create less charcoal.

A further important factor affecting charcoal yield is combustion temperature, and its rate of change. Chrzazvez et al. 2014 reports lower conversion rates at 750°C than 400°C; likewise Pastor-Villegas et al. 2007 (250-1000°C), and Stimely and Blankenhorn 1985 (250-600°C), representing c.5-15% of the charcoal yield. However, whilst lower temperatures create more charcoal, charcoal created at 500°C+ decomposes less post-combustion, although denser lower-temperature charcoal fragments less (Braadbaart and Poole 2008, 2009, Mooney and Tinner 2000, Vaughan and Nichols 1995). Anticorrelated conversion rates and charcoal stability at given temperatures might negate many temperate-related conversion rate biases. Combustion temperature may be taxa-dependent if certain fuelwoods attain higher temperatures (Thery-Parisot et al. 2018). However, many other factors are involved, including burning multiple taxa together, firebuilding skill, fire management choices, burning fires to completion or not, wind speed to fan flames (or exert cooling effects – Wolf et al. 2013), condition/moisture content of fuelwood and desired temperatures for technological applications (e.g. cooking). Thus temperature-induced variables in charcoal yields probably do not correlate with the taxa burnt.

Optimizing wood-to-charcoal conversion rates has long been important, initially for charcoal-burning, and more recently to create charcoal for medical procedures, filtration and biofuels. Many studies found conversion rates of 1.3-22% charcoal yield by weight of original wood (Kurosaki et al. 2003). However, higher yields burn in optimized anaerobic conditions, or use synthetic catalysts, so lower yields are more accurate for archaeological contexts. It is of course impossible to correlate charcoal records to original wood input *quantities*, only *proportions*. Certain taxa such as *Arbutus, Carpinus* and *Fagus* are traditional charcoal-producers (Delhon et al. 2017, Moser et al. 2018); others like *Abies, Acer, Populus* and *Salix* are avoided for perceived poor conversion rates (Paysen 2012). Early 19th century studies found inter-species conversion rates varying by up to 9% (Ure 1824), and Frejaville et al. (2013) support these conclusions. However, Thery-Parisot et al. (2018) refute this, claiming all taxa have near-identical charcoal yields.

Their view has been generally followed in suggesting that differential charcoal production is not an issue in charcoal analysis and interpretation. Nonetheless, the frequent counter-view is also voiced, especially in more traditional studies. I believe that the difference may be explained thus: in modern experiments, Thery-Parisot and colleagues (whose methodology I follow) burnt wood under optimized anaerobic conditions, finding little variability for their studied genera. However, traditional charcoal-burners, whilst optimizing to a degree, could not create proper anaerobic environments or constant heat sources, and thus their anecdotal findings may better represent real-life conditions. My own experiments, as described in Chapter Seven, supports the concept of different genera-specific conversion rates. In open-fire settings, differences may still exist because of differential conversion rates *under suboptimal settings,* different wood densities and oxygen availability by taxa, and different heats reached. Indeed, "natural" charcoal is 10-40% smaller and narrower than lab-produced samples, with much more ash created instead (Umbanhowar and McGrath 1998). However, open-air experiments are challenging for collecting and measuring charcoal without encountering other issues relating to fragmentation and collecting/counting techniques. As I separate conversion from any other taphonomic issues, this approach would be impractical. By following Thery-Parisot's experiment, extended to a wider number of taxa, I better understand how different woods operate under a variety of conditions.

I.I: Experiment 1 (Conversion Rate): Methodology.

Wood samples representing the 25 genera found in selected Middle Palaeolithic Iberian sites were obtained. In addition, I chose wood from a further 17 genera; these are found in an additional 24 Neanderthal sites with complete charcoal diagrams (see Map 6.1). Given that each genus has several subspecies, a representative species, always the most likely to have been present in Neanderthal environments (as stated in publications), was chosen.

Table 6.1: The representative species chosen for each genus for Experiment 1.

Genus	**Representative species used**	**Common Name**
Acer	*Acer campestre*	Field Maple
Alnus	*Alnus glutinosa*	Black Alder
Amygdalus	*Amygdalus prunus*	Almond Tree
Arbutus	*Arbutus unedo*	Strawberry Tree
Betula	*Betula pendula*	Silver Birch
Buxus	*Buxus sempervirens*	Common Box
Carpinus	*Carpinus betulus*	European Hornbeam
Castanea	*Castanea sativa*	Sweet Chestnut
Celtis	*Celtis bungeana*	Bunge’s Hackberry
Cornus	*Cornus sanguinea*	Common Dogwood
Corylus	*Corylus avellana*	Common Hazel
Crataegus	*Crataegus monogyna*	Common Hawthorn
Cytisus	*Cytisus scoparius*	Common Broom
Erica	*Erica vagrans*	Cornish Heather
Fagus	*Fagus sylvatica*	Common Beech
Ficus	*Ficus carica*	Common Fig
Fraxinus	*Fraxinus excelsior*	European Ash
Hedera	*Hedera helix*	Common Ivy
Hippophae	*Hippophae rhamnoides*	Sea Buckthorn
Ilex	*Ilex aquifolium*	Common Holly
Juglans	*Juglans regia*	Common Walnut
Juniperus	*Juniperus communis*	Common Juniper
Larix	*Larix decidua*	European Larch
Laurus	*Laurus nobilis*	Bay Laurel
Olea	*Olea europeae*	Common Olive
Phillyrea	*Phillyrea latifolia*	Mock Privet
Picea	*Picea abies*	Norway Spruce
Pinus	*Pinus sylvestris*	Scots Pine
Pistacia	*Pistacia chinensis*	Chinese Pistache
Populus	*Populus alba*	White Poplar
Prunus	*Prunus avium*	Wild Cherry

Genus	**Representative species used**	**Common Name**
Pyrus	*Pyrus communis*	Wild Pear
Quercus	*Quercus petraea/Quercus Ilex*	Holm Oak
Rhamnus	*Rhamnus cathartica*	Purging Buckthorn
Salix	*Salix atrocinerea*	Grey Willow
Sambucus	*Sambucus nigra*	Elder Tree
Sorbus	*Sorbus aria*	Whitebeam
Tamarix	*Tamarix ramosissima*	Saltcedar Tamarisk
Taxus	*Taxus baccata*	English Yew
Ulex	*Ulex europaeus*	Common Gorse
Ulmus	*Ulmus minor*	Field Elm
Viburnum	*Viburnum tinus*	Laurestine

Map 6.1: The locations of the additional 24 Middle Palaeolithic sites with published anthracological diagrams.

I followed common experimental methodologies (Chrzazvez et al. 2014, Dussol et al. 2017, Lancelotti et al. 2010, Lennox et al. 2017, Thery-Parisot and Henry 2012). Wood was gathered from one of three contexts:

1) The following genera were obtained from wild landscapes, with an attending botanist to ensure correct species identification: *Acer, Alnus, Betula, Carpinus, Castanea, Corylus, Crataegus, Erica, Fagus, Fraxinus, Hedera, Hippophae, Ilex, Larix, Picea, Pinus, Populus, Prunus, Quercus, Rhamnus, Salix, Sambucus, Sorbus, Ulex, Ulmus.*
2) The following genera were obtained from domestic gardens or purchased from garden centers. Here, all trees were already tagged to identify their species and genus:

Amygdalus, Arbutus, Buxus, Cornus, Cytisus, Ficus, Juglans, Juniperus, Laurus, Olea, Pyrus, Tamarix, Taxus, Viburnum.

3) The following genera were obtained from the Royal Botanic Gardens, Edinburgh, provided and identified by the garden curators: *Celtis, Phillyrea, Pistachia.*

- I used exclusively healthy dry deadwood. To determine health, sawed wood was visually inspected to exclude flaws, knots and diseased/rotten areas, including ash dieback. This ensured that all samples within a set were identical, and that primary inter-group differences came from morphological/chemical differences by genus rather than by condition.
- All wood was fully dried, so that the only moisture content differences were those found between natural dry woods, and not a product of using green versus dry wood. My wood samples were subsequently left in a dry room for 3 months (ambient humidity c.30-50%) to simulate natural drying, as kiln-drying introduces further artificial changes such as hardening. Frejaville et al. (2013) used natural temperatures for drying, but only for 72h; all other burning studies artificially dried their wood (Prior and Alvin 1983, Prior and Gasson 1993, Moore et al. 1974).
- Dried wood was sawn into debarked core wood cubes of 8cm^3, 2cm on each edge. These samples represent "optimal" Neanderthal fuels which have been carefully curated and dried. 8cm^3 best represents the diameter of small deadwood branches, and was used by Chrzazvez et al. (2011, 2014). Smaller sample volumes were used by Moore et al. (1974), Prior and Alvin (1983), Prior and Gasson (1993), Kwon et al. (2014) and Braadbaart et al. (2009), and larger ones by Thery-Parisot and Henry (2012). Larger volumes better represent large logs, however given that Neanderthals foraged for smaller branches as deadwood, 8cm^3 best represents these branch diameters (Allue et al. 2012).
- The exceptions were *Celtis, Phillyrea* and *Pistacia*, which were obtained as smaller branches and burnt as smaller complete branch samples to obtain enough wood mass.
- Prior to burning, each wood cube sample was weighed to determine its mass.

Samples of all genera were burned in a Carbolite GSM 11/8 Muffle Furnace (UCL Geography Laboratory) at 350°C and 700°C for 1 hour, in tin foil (350°C) or sand (700°C) in crucibles. The former temperature represents close to optimal charcoal conversion temperatures of open fires (Stimely and Blankenhorn 1995); the latter represents the upper temperature range of open fires (Prior and Gasson 1993).

4) Chrzazvez et al. (2014) and Prior and Gasson (1993) only burnt their samples for 30 minutes; my burning for 1h (as done by Braadbaart and Poole 2008, Nichols et al. 2000, Prior and Alvin 1983, Henry 2012) safely exceeds that, ensuring the samples are fully burnt.
5) Excluding oxygen through tin foil wrappings follows Lancelotti et al. (2010). Foil's melting point is c.660°C; as the 700°C experiments would have caused degradation and possible sample contamination, I instead put these samples in sand-filled crucibles, following Prior and Alvin (1983) and Prior and Gasson (1993). Using pure nitrogen atmospheres to exclude oxygen (as used by Braadbaart 2004, Braadbaart and Poole 2008, Braadbaart et al. 2009, Kwon et al. 2014, Moore et al. 1974) was impractical in this experimental setup.
6) Each subset used 10 samples per taxa; for a total of 840 samples for this experiment.
7) The samples were subsequently weighed, and mass loss calculated as a percentage of the original weight, and the mean of these 10 samples calculated.

II: Fragmentation Rate.

As well as differential charcoal production, differential charcoal fragmentation can cause significant error. Natural sedimentation taphonomy can cause fragmentation: sediment pressure, frost-thaw cycles, trampling, movement abrasion and root damage (Allue and Mas 2020, Carcaillet 2001, Carcaillet and Talon 1996). Once splitting begins, sediment grains infiltrate charcoal structures and exacerbate the problem (Allott 2006). However recovery processes, in particular flotation, also cause fragmentation. Charcoal becomes hydrophilic through oxidation processes over time (Arranz-Otagui 2017), causing further fragmentation from water influx. Such charcoal quickly waterlogs and sinks, causing further bias. Flotation decreases the diversity of taxa recovered (Allue and Mas 2020), suggesting that different taxa react differently to it. However, flotation causes notably less fragmentation than other forms of recovery such as hand-picking (Kabukcu and Chabal 2020); this latter practice should be avoided, as it is biased towards obvious, larger fragments.

A natural cause of differential fragmentation is the wood itself. Carbonization preserves density ratios (Chrzazvez et al. 2014) so denser woods create denser charcoals (though see Braadbaart and Poole (2008) for a counter-view). Denser charcoals resist parallel fibre compressions better, and have higher strength moduli (Assis et al. 2016), albeit with less compressive resistance than diffuser, spongier charcoals (Lancelotti et al. 2010). Denser woods (and denser charcoals) fragment more in compressive sediment trampling, but resist knocks and breakage during recovery processes. Furthermore, wood density varies throughout growing seasons, and latewood charcoal (dense wood produced later in growing seasons) is more resistant to fragmentation than earlywood charcoal (Kaiser et al. 2009). Thus, earlywood charcoal of "dense" genera may fragment more than tougher latewood charcoal of softwood genera.

Aspects of wood other than density also contribute to charcoal friability. With regards to this experiment, burning in foil may create more structurally stable samples than in sand; however all samples tested at 350°C were created in foil. Xylem ray cells are weak, and wide-rayed taxa like *Quercus* split more (Prior and Alvin 1983). Certain resinous taxa like *Pinus* resist fragmentation as resin binds the cells together. Growth rings form weak points (Scott 1989); thus older trees suffer from more charcoal fragmentation. This correlates to genus, as slower-growing genera like *Taxus* have more growth rings than faster-growing taxa like *Fagus* by the time they reach a sufficient height for harvesting, and thus fragment more. However, given most fuel comes from dead branches rather than main trunks, tree ages are less relevant than ages of harvested branches. However, taxa with fast-growing and fast-shedding branches like *Pinus* will still have less growth rings than slower-growing *Quercus* branches. In addition, wood *condition* is as important for fragmentation as taxa-specific structures. Wet (rotten and green) woods fragment more when burnt, as cracks form as high-pressure steam escapes (Figueiral 1995b, though Thery-Parisot and Henry (2012) gives an alternative view). Whilst wood condition somewhat correlates with genera-specific rates of drying and decay, if we assume the Principle of Least Effort, in practice some cultural choice of wood state always occurs.

Finally, production temperature also affects charcoal's strength and fragmentation (Dias Jr et al. 2016, Scott and Jones 1991). We have already examined how production temperature affects wood-to-charcoal conversion rates; similar patterns can also be observed for charcoal's strengths. Zickler et al. (2006) claims that "charcoal hardness" rises quickly with heat to 700°C, then slowing to 1000°C before declining. It is unclear how this hardness value corresponds to fragmentation, as harder charcoals may fragment more or less, depending on pressure patterns. This counters Braadbaart and Poole's 2008 findings, which found that higher-temperature charcoal was more porous, less dense and more prone to fragmentation than charcoal formed at lower temperatures. Other authors claim that charcoal's compressive strength decreases up to 500/600°C, before increasing again (Assis 2016). These apparently conflicting views reconcile if charcoal's porosity and density decrease but charcoal's inherent carbon bonds strengthen as production temperature increases. Large pieces would fracture more easily along lines of weakness, but subsequently, increased inherent strengths would prevent further fragmentation. However, Dussol et al. (2017) claim that intrinsic species differences are far more important to subsequent fragmentation than production temperature.

It may be questioned why fragmentation matters, as unlike charcoal production it does not innately affect taxa representation, except when fragments are too small to be properly identified, or slip through sieves (usually only pieces 2mm+ are analysed – Chabal 1988, 1992). However, almost all studies count fragments to quantify genera proportions (e.g. Whitau et al. 2017a). Differential fragmentation obviously biases this method, as highly-fragmenting genera appear grossly overrepresented (Belcher et al. 2013). Alternative quantification methods, such as mass and volume, are preferable but much harder to undertake. Volume is difficult to quantify accurately on small pieces (ways include multiplying shortest/longest axes, or immersing in known volumes of fine sand – Novak et al. 2012, Lancelotti et al. 2010), and mass is questionable as porous charcoals have mineral uptake, causing disproportionate weights (Kabukcu 2015). Ali et al. (2009) and Leys et al. (2013) claim that charcoal mass and fragment number are well-correlated, as although some charcoals fragment more, theoretically creating more pieces, these pieces in turn quickly fragment to sizes too small to study, balancing out different fragmentation rates (Dotte-Sarout et al. 2015, Henry et al. 2020). Despite this, differential fragmentation is an important issue, and despite potentially having many variables, I examine whether it can have a statistically significant effect.

II.I: Experiment 2 (Fragmentation Rates): Methodology.

I followed methodologies by Chrzazvez et al. (2014) and Lancelotti et al. (2010).

- Ten samples for each genus, created at 350°C, were placed together in a sealed sample bag (to prevent fragment loss) at randomized orientations, to ensure random parallel or perpendicular fibre crushing. These bags were crushed under a 56lb (25.4kg) weight dropped from 5cm, representing standardized trampling.
- Fragmented samples were dry sieved through nested sieves, of 1mm, 3mm, and 6mm mesh diameter. 1mm represents smallest mesh sizes used in sites (e.g. Pop et al. 2016 at Neumark-Nord), 3mm represents the smallest size (2-4mm) accurately identifiable to genus level (Figueiral and Mosbrugger 2000), and 6mm represents a larger size reliably spotted during hand-picking. Although 2mm and 4mm sieves are common, 3mm is also used in many studies (e.g. Allue and Mas 2020, Bachelet and Scheel-Ybert 2017, Bodin et al. 2020, Dotte-Sarout and Kahn 2017, King and Dotte-Sarout 2019, Ortiz et al. 2017, Puech et al. 2021, Scheel-Ybert and Bachelet 2020, Zwane et al. 2023). 3mm represents the largest that single growth-rings of charcoal can grow (Bernard 1998, Dufraisse et al. 2018, Kabukcu et al. 2021), and is an important cut-off size as growth-rings frequently separate as charcoal (Rossen and Olson 1985). 6mm is likewise a commonly used size for the largest fragments (e.g. Brossier and Poirier 2018, Paradis-Grenouillet et al. 2009, Shirazi and Shirazi 2012).
- The 3mm+ fragments were counted, and weighed together, and those 1-3mm were only weighed (as >700 <1mm fragments were produced in test fragmentations). From this, I could also determine the mass of the lost <1mm fraction.

The methodologies outlined in Experiment 1 were tested with *Malus* (apple) wood, from known specimen plants who had been observed for several years (spp. *domestica*, Kent). The results in Table 6.2 below suggest that oxygen-excluding methods minimally affect conversion rates, provided they are effective. I did not test nitrogen atmosphere methods used by some researchers, due to time and equipment constraints, and cannot comment on their effectiveness. Likewise, sample volumes (and therefore masses), and burning durations, do not greatly affect conversion rates. However, heartwood created significantly more charcoal (34.7%) than otherwise-identical sapwood (27.1%) – (p = 0.0005887). This suggests that tree parts burnt determine conversion rates, possibly because heartwood is denser and drier than sapwood. All my other samples came from standardised exterior branch sapwood, and thus probably represent minimum conversion rates.

Table 6.2: Results of experimental procedure testing on *Malus* wood, showing similarities between different burning procedures and lengths, but differences between sapwood and heartwood.

***Malus* Burning Method (350°C)**	**Wood-to-Charcoal Conversion Rate (%)**	**Range**	**Standard Error**
Foil, 1h	27.1	13.1	1.4211
Foil (1/8 size sample), 1h	28.209	12.21	1.0967
Foil, 2h	29.482	6.23	0.7361
Sand, 1h	29.9038	7.83	1.1273
Foil, 1h, Heartwood	34.6589	3.16	0.3506

When I changed the furnace temperature, conversion rates drastically dropped from 250-350°C, but dropped more slowly at still higher temperatures (see Table 6.3 for significance tests). This suggests that although increasing temperatures decrease charcoal yield, 250-350°C is the key threshold for full charcoalification. I was unable to test burning in foil to 700°C as the aluminium foil would have melted at 660°C and adhered to the charcoal. 500°C was therefore the top temperature I could attain without compromising the foil's integrity. Few fires burn lower than this while still creating flames and light. Whilst Neanderthal fires would of course have left unburned portions of wood behind, 1) these may have been burnt in subsequent fires and 2) they would have been destroyed by bacterial/chemical degradation that charcoal was safe from, and thus are absent from the archaeological record. Thus only charcoal created above c.300/350°C is of archaeological value, as most created at 250°C would subsequently be lost.

Table 6.3: Effects of different temperatures on wood-to-charcoal conversion rate for *Malus*. The largest loss is from 250-350°C, and subsequently decreases more slowly to 550°C. This is also presented in Graph A38, p.405.

***Malus* Burning Temperature (Foil, 1h)**	**Wood-to-Charcoal Conversion Rate (%)**	**Range**	**Standard Error**	**Welch's T-test significance and p values between temperature values and the value above**
250°C	79.986	15.01	1.9187	Yes (p = 1.685e-13)
350°C	27.1	13.1	1.4211	Yes (p = 0.008225)
450°C	22.156	2.41	0.2511	Yes (p = 0.001258)
550°C	20.94	1.68	0.1886	No higher value to test against

III: Experimental Testing Results.

When I tested *Malus* samples burnt in sand at 700°C, I manually separated organic residues from the sands. This was due to potential unknown mass losses of the sand itself from combustion of any organic residues in it (despite prior heating to remove as much as possible). This introduced potential experimental error, but I used identical tweezers for all samples, and timed myself for 10 minutes searching through each sample for charcoal. This ensured equal thoroughness on all samples. Samples degrading into finer ash particles were more likely to be missed, but conversely also more likely to have included sand in its interstices, falsely increasing its weight. Intermingling of sand into these ashy matrices make these weight measurements less reliable than for those test pieces burned in sand at 350°C, where the charcoal was solid and sand couldn't enter. However, this issue is present in all archaeological charcoal.

On testing fragmentation rates, *Malus* charcoal split into 557 counted fragments >3mm, with a 1:2.46 ratio of >6mm to 3-6mm fragments, with 6.88% of the charcoal <1mm and thus lost from the system. The initial test showed the necessity of excluding air from the sealed bag, as the bag became pressurised, potentially protecting the specimens. Flattening and removing air pre-sealing prevented this. The charcoal tended to split along the fibres, creating individually fibred or bundled multifibre charcoal of an approximate 3:1 ratio length to width. Doubtless, this charcoal would further fragment cross-fibre if subjected to further crushing, however the wood tended to initially split along rather than across the fibre. This suggests that charcoal has higher compressive strengths (and thus lower fragmentation rates) if crushed transversally, as opposed to radially or tangentially.

IV: Conclusion.

These two experiments intend to address the primary concerns that differences between Middle Palaeolithic charcoal and pollen record is due to charcoal-related taphonomic bias, both in its production (Experiment 1) and subsequent fragmentation (Experiment 2). If, following recalibration, differences between the values tends towards 0, it would suggest that this bias is indeed the primary cause; if however they remain constant, or discrepancies increase, then alternatives must be suggested, the most likely of which is active Neanderthal selection. The following chapter addresses these questions.

Chapter Seven: Results.

I.I: Conversion Rate Experiment Results (350°C)

At 350°C, all genera tested created reliable charcoal, in almost-perfect cubes, with the exception of *Celtis*, *Phillyrea* and *Pistacia*, which were only available as smaller cylindrical barked samples (see Chapter Six, p.167). The conversion appeared complete, with no unburnt or partially-charred wood on cutting open random samples, which were then excluded from the fragmentation experiments. All samples were burnt for longer (1h) than charring requires (c.20 minutes). Initially, two samples of each ten-sample set created much more charcoal than expected (>50% conversion rate) due to insufficient oven entrance sealing causing lower local temperatures there; these were re-calculated, and subsequent samples all placed nearer the back, where regular carbonization occurred.

The complete absence of ash from all samples suggests that at this temperature, ash production is negated in favour of charcoal. This also suggests that all non-charcoalified material was combusted, or lost as water vapour or other fumes. The foil wrapping may of course have hindered vapour loss, artificially increasing charcoal masses, but this is inherent to all oxygen-excluding solutions, excluding the nitrogen atmosphere which of course would not be present in real-life samples. In real woods, exterior wood may hinder water loss and cause similar conditions. Testing samples immediately after burning prevented atmospheric water vapour re-entering; water may re-percolate into archaeological charcoal of course, but mostly from flotation and wet sieving. Condition also impacts charcoal production rates; rotten *Fraxinus* yielded 30.44% charcoal, as opposed to 27.34% for fresh healthy *Fraxinus*. As sample sizes of rotten and fresh *Fraxinus* were unequal due to excluding some samples, a two-sample t-test (see p.145) found that this difference was extremely significant ($p = 0.00002778$). Rotten wood might have higher moisture contents, which when lost in burning creates lower conversion rate than fresh wood. The fact that charcoal conversion rates of rotten wood are higher further suggests that products of decay are more resistant to fire and/or prevent oxygen intake more effectively than fresh wood. The results presented below in Table 7.1 show varying conversion rates of 22.8% to 42.3%; full experimental results are in Appendix Three.

Table 7.1: Wood-to-Charcoal conversion rates at 350˚C. Compared to pine as an common value of 1, other woods create from 0.66x-1.23x charcoal mass (per unit mass of fuel) compared with pine.

Genus	**Wood-to-Charcoal Conversion Rate at 350°C (%)**	**Relative Conversion (compared to *Pinus* = 1)**	**Standard Error (%)**	**Standard Error for Relative Conversion (compared to *Pinus* = 1)**
Fagus	22.841	0.6608	0.5993	0.0227
Arbutus	24.371	0.7050	0.5828	0.0295
Ilex	24.446	0.7072	0.5401	0.0289
Betula	25.469	0.7368	1.2525	0.0442
Cornus	25.78	0.7458	0.8168	0.0348
Olea	25.799	0.7463	0.5501	0.0302
Quercus (deciduous)	26.035	0.7532	0.5762	0.0308
Salix	26.456	0.7653	0.6779	0.0328
Carpinus	26.756	0.7740	0.4541	0.0296
Corylus	27.245	0.7882	0.5686	0.0317
Alnus	27.275	0.7890	0.5722	0.0317
Fraxinus	27.3425	0.7910	0.3870	0.0293
Ficus	27.541	0.7967	0.2882	0.0286
Quercus (average)	27.6225	0.7991	0.6402	0.0331
Acer	27.94	0.8083	0.6439	0.0334
Celtis	28.029	0.8108	0.5621	0.0322
Juglans	28.347	0.8200	0.5721	0.0326
Crataegus	28.409	0.8218	0.4277	0.0308
Salix-Populus (average)	28.5235	0.8251	0.7337	0.0354
Pyrus	28.856	0.8348	1.0316	0.0414
Viburnum	28.941	0.8372	0.7346	0.0357
Cytisus	29.028	0.8397	0.4804	0.0320
Quercus (evergreen)	29.21	0.8450	0.9157	0.0393
Amygdalus	29.852	0.8636	0.7308	0.0364
Sorbus	29.949	0.8664	0.8407	0.0384
Pistacia	29.998	0.8678	0.4472	0.0325
Ulmus	30.045	0.8692	0.9970	0.0415
Sambucus	30.243	0.8749	0.4196	0.0324
Ulex	30.287	0.8762	0.7481	0.0370
Populus	30.591	0.8850	0.9294	0.0406
Hedera	31.104	0.8998	0.7534	0.0378
Buxus	32.31	0.9347	0.7559	0.0388
Prunus	33.396	0.9661	0.8927	0.0420

Genus	**Wood-to-Charcoal Conversion Rate at 350°C (%)**	**Relative Conversion (compared to *Pinus* = 1)**	**Standard Error (%)**	**Standard Error for Relative Conversion (compared to *Pinus* = 1)**
Hippophae	33.588	0.9717	0.5018	0.0364
Tamarix	34.163	0.9883	0.8301	0.0416
Rhamnus	34.244	0.9906	0.3981	0.0359
Picea	34.3	0.9922	0.969	0.0441
Erica	34.493	0.9978	1.0292	0.0454
Pinus	34.568	1.0000	1.1863	0.0485
Laurus	34.887	1.0092	1.2234	0.0495
Phillyrea	34.929	1.0104	0.9101	0.0435
Juniperus	35.599	1.0298	0.8292	0.0427
Picea/Larix	36.993	1.0702	0.9100	0.0452
Castanea	37.376	1.0812	2.4358	0.0796
Larix	39.686	1.1481	0.9725	0.0484
Taxus	42.345	1.2250	3.5627	0.1113

The mean laboratory conversion rate of 30.37% is of course far higher than real-life hearth conversion rate, given the amount recovered compared to known fuel inputs. This is because these experiments were consistently at optimum temperatures (whilst real fires would also be subject to higher temperatures), but the samples were fully excluded from oxygen, which would apply only to the centre of larger fuel pieces in real life. Thus the conversion rates themselves will not be replicated in the archaeological record, but the relative values between the different genera should be. A source of real-life variation will be branch morphology and diameter, as larger diameters have increased likelihoods of charcoalification. However given branches in Neanderthal firepits would have been gathered rather than cut, branch morphology will be highly variable and depend less on genera morphology.

I.II: Conversion Rate Experiment Results (700°C)

At 700°C, charcoal yields sharply dropped, sometimes being almost non-existent (see Table 7.2 beneath). Only *Castanea* and *Taxus* produced large charcoal fragments, although very friable and with some intermingled ash. *Erica* and *Larix* created strange yellowy-brown ashy substances, with some embedded darker charcoal strands; all other genera created mostly white ash, extremely soft and friable, with minimal charcoal (though a little was found for *Viburnum*). Due to the impossibility of separating commingled charcoal and ash samples, except through uncontrollable taphonomic processes through time, I weighed both together. However, I think that only *Castanea, Taxus* (and potentially *Erica*) might produce large enough charcoal pieces at 700°C for reliable identification (2mm being the smallest identifiable charcoal size). The different nature of the *Celtis, Phillyrea* and *Pistacia* samples, due to their small size, circular shape and barking (and small sample sizes in the case of *Pistacia*) may account for their relatively high yields. Here, ash was compacted within the charcoalified bark; when dropped, this fractured into similarly sized and friable pieces as other woods, so this phenomenon may just result from delicate handling, and not occur archaeologically. Both *Rhamnus* and *Laurus* created no charcoal, suggesting that all charcoal we find of these genera must result from lower temperatures.

Table 7.2: Wood-to-charcoal conversion rates at 700°C. These vary much more than at lower temperatures, with various woods creating 0.59x-19.51x the charcoal mass that pine does.

Genus	**Wood to Charcoal-Ash Conversion Rate at 700°C (%)**	**Relative Conversion (compared to *Pinus* = 1)**	**Standard Error (%)**	**Standard Error for Relative Conversion (compared to *Pinus* = 1)**
Hippophae	0.343	0.5904	0.1052	0.2017
Fraxinus	0.393	0.6764	0.2123	0.3793
Pinus	0.581	1.0000	0.0876	0.2133
Juniperus	0.808	1.3907	0.0965	0.2674
Corylus	1.28	2.2031	0.3436	0.6782
Salix	1.365	2.3494	0.3394	0.6832
Fagus	1.384	2.3821	0.1635	0.4562
Salix-Populus	1.4205	2.4449	0.1910	0.4941
Acer	1.444	2.4854	0.2630	0.5875

Genus	**Wood to Charcoal-Ash Conversion Rate at 700°C (%)**	**Relative Conversion (compared to *Pinus* = 1)**	**Standard Error (%)**	**Standard Error for Relative Conversion (compared to *Pinus* = 1)**
Populus	1.476	2.5404	0.1952	0.5094
Quercus (deciduous)	1.517	2.6110	0.1296	0.4525
Larix	1.65	2.8399	0.1500	0.5001
Ulmus	1.674	2.8812	0.4948	0.9560
Betula	1.722	2.9639	0.1740	0.5377
Ilex	1.834	3.1566	0.3075	0.7121
Carpinus	1.871	3.2203	0.1270	0.5326
Quercus (average)	1.9185	3.3021	0.1636	0.5719
Taxus	2.087	3.5921	0.5519	1.0934
Prunus	2.088	3.5938	0.2516	0.6936
Sorbus	2.106	3.6248	0.2975	0.7492
Olea	2.271	3.9088	0.1637	0.6536
Quercus (evergreen)	2.32	3.9931	0.2457	0.7359
Amygdalus	2.6122	4.4960	0.1147	0.7063
Buxus	2.635	4.5353	0.1983	0.7642
Picea/Larix	2.692	4.6334	0.3391	0.9105
Pyrus	2.697	4.6420	0.1385	0.7395
Cytisus	2.73	4.6988	0.1662	0.7640
Alnus	2.7444	4.7236	0.7761	1.5139
Ulex	2.7567	4.7448	0.1203	0.7449
Crataegus	2.944	5.0671	0.1130	0.7884
Juglans	3.213	5.5301	0.1792	0.8892
Phillyrea	3.28	5.6454	0.3503	1.0433
Viburnum	3.401	5.8537	0.2885	1.0127
Castanea	3.656	6.2926	0.6861	1.5153
Picea	3.734	6.4269	0.4707	1.2635
Cornus	4.084	7.0293	0.3296	1.2020
Tamarix	5.128	8.8262	0.4459	1.5366
Hedera	5.34	9.1910	0.6211	1.7500
Arbutus	6.204	10.6781	0.5077	1.8324
Pistacia	6.26	10.7745	----------------	---------------------
Erica	7.129	12.2702	0.4658	2.0160
Sambucus	7.225	12.4355	0.5186	2.0767
Ficus	8.387	14.4355	0.3360	2.2519
Celtis	11.3344	19.5084	0.7609	3.2208

Rhamnus and *Laurus* excluded (no charcoal created).

The average conversion rate of 3.04 likewise does not represent actual conversion rates for Neanderthal fires; rates might be lower if conditions are not perfect anaerobic, or higher if the fires are not constantly at the low conversion temperature of 700°C. However these experiments still give useful indications of relative differences between genera, although these are not independent of temperature (as *Pinus* produces one of the lower percentages of charcoal at 700°C compared to one of the higher percentages at 350°C).

Burning both *Quercus petraea* and *Quercus ilex* allowed me to sample a deciduous and an evergreen oak species respectively. Many anthracological diagrams differentiate between *Quercus* deciduous and *Quercus* evergreen, sometimes including both separately on the same diagram (e.g. El Salt – Vidal-Matutano et al. 2017). When *Quercus* is distinguishable as deciduous or evergreen, I use the respective conversion rate; otherwise I use the average. Likewise, where *Salix*/*Populus* and *Picea*/*Larix* are listed together, due to an inability to distinguish between charcoal morphologies, I average these two genera's conversion rates. When viewed independently of anthracological data, the varying conversion rates show several trends, one notably being differences between deciduous trees, evergreen and conifers (Table 7.3, below).

Table 7.3: Average wood-to-charcoal conversion rates correlated with the broader tree type.

Type of Tree	**Genera**	**Wood-to-Charcoal Conversion Rates at 350˚C**	**Wood-to-Charcoal Conversion Rates at 700˚C**
Evergreens	*Arbutus, Buxus, Erica, Ficus, Hedera, Ilex, Laurus, Olea, Quercus* evergreen, *Phillyrea, Pistacia, Ulex, Viburnum*	24.371, 32.31, 34.493, 27.541, 31.104, 24.446, 34.887, 25.799, 29.21, 34.929, 29.998, 30.287, 28.941 (average = 29.8705)	6.204, 2.645, 7.129, 8.387, 5.34, 1.834, 2.271, 2.32, 3.28, 6.26, 2.7567, 3.401 (average = 4.3190)
Deciduous	*Acer, Alnus, Amygdalus, Betula, Carpinus, Castanea, Celtis, Cornus, Corylus, Crataegus, Cytisus, Fagus, Fraxinus, Hippophae, Juglans, Populus, Prunus, Pyrus, Quercus* deciduous, *Rhamnus, Salix, Sambucus, Sorbus, Tamarix, Ulmus*	27.94, 27.275, 29.852, 25.469, 26.756, 37.376, 28.029, 25.78, 27.245, 28.409, 29.028, 22.841, 27.3425, 33.588, 28.347, 30.591, 33.396, 28.856, 26.035, 34.244, 26.456, 30.243, 29.949, 34.163, 30.045 (average = 29.1702)	1.444, 2.7444, 2.6122, 1.722, 1.871, 3.656, 11.3344, 4.084, 2.944, 2.73, 1.384, 0.393, 0.343, 3.213, 1.476, 2.088, 2.697, 1.517, 1.365, 7.225, 2.106, 5.128, 1.674 (average = 2.8587)
Conifers	*Juniperus, Larix, Picea, Pinus, Taxus*	35.599, 39.686, 34.3, 34.568, 42.345 (average = 37.2996)	0.808, 1.65, 3.734, 0.581, 2.087 (average = 1.772)

Whilst evergreens and deciduous trees have statistically-similar conversion rates at 350°C, conifers have higher conversion rates, due to resins creating more reducing conditions during combustion, and resin not being fully combusted at 350°C – although some must be burnt, to account for the brightness and high Fuel Value Index (FVI) of conifers even in low-temperature fires. This indicates that conifer charcoal still contains much resin. However, by 700°C, this resin has clearly been burnt off as conifers show the lowest conversion rates, suggesting that resin no longer plays a part, and the otherwise soft, loose nature of conifer woods causes low wood-to-charcoal conversion rates. As expected, denser evergreens have higher conversion rates than deciduous trees at 700°C, once again correlating with density. Density values can be found later in this chapter on p.187, and also in Appendix Six, p.387.

II: Comparison with other studies.

This experiment is not unique in its methodology or aims, although encompassing many more samples and genera. Other similar papers include Chrzazvez et al. (2014), Feurdean (2021), Frejaville et al. (2013), Hudspith et al. (2018), Rossen and Olson (1985) and Thery-Parisot et al. (2014). Comparisons demonstrate many trends exist throughout all studies, especially the high conversion rates of conifers compared to broadleaf trees. Conversion rates themselves often vary, due to differing experimental methodologies, further indicating that precise conversion rates themselves are produced by my methodology, but that relative rates of different genera are consistent, and usable for reliable recalibration.

II.I: Frejaville et al. 2013.

When compared to Frejaville et al (2013), several similarities are noted. Actual conversion rate values differ immensely; for the same genera, Frejaville notes conversion ranges of 25-72%, whilst I have a 25-39% range. This can be expected for the lower temperature burnings of Frejaville's samples however (215°C), as my test *Malus* samples at 250°C showed a c.80% conversion rate, consistent with Frejaville's *Larix* samples, which I took to indicate incomplete combustion. Additionally, Frejaville's samples were barked whereas mine were debarked, causing further discrepancies. However, despite this and differences within sample sets, several similarities occur. In both sets, *Betula* and *Salix* are almost identical, as are *Pinus* and *Picea*. Likewise, conifers consistently produce more charcoal than broadleaf woods. In both there is a pronounced divide between broadleafs and conifers, and *Larix* makes consistently more charcoal than any other genus. Both studies therefore arrive at similar conclusions, and differences noted are mainly methodological, including Frejaville's lower temperature burnings, which I believe led to incomplete combustion. Percentage conversions with comparison to *Pinus* shows near-identical results for *Betula, Picea* and *Salix,* all within the standard errors for my samples (for relative conversion rates), and similar ones for *Larix*. However *Sorbus* has notably lower relative conversion rates in Frejaville's samples than in mine. Calculating the relative orderings of the different genera from low-to-high charcoal production, irrespective of actual or relative conversion rates, many similarities emerge ($R^2 = 0.5951$, $p = 0.0724$), suggesting that the different genera are somewhat similarly consistently good or bad charcoal producers.

Table 7.4: Comparing Frejaville's (2013) and my (2023) findings. This is also presented on Graph A39, p.405.

Frejaville's findings (215°C) – Genus and conversion rate (%)		**Relative Conversion (compared to *Pinus* = 1)**	**My findings (350°C) – Genus and conversion rate (%)**		**Relative Conversion (compared to *Pinus* = 1)**
Sorbus	25%	0.4386	*Betula*	25.469	0.7368
Betula	41%	0.7193	*Salix*	26.456	0.7653
Salix	42%	0.7369	*Sorbus*	29.949	0.8664
Pinus	57%	1.00	*Picea*	34.3	0.9922
Picea	58%	1.0175	*Pinus*	34.568	1.00
Larix	72%	1.2632	*Larix*	39.686	1.1481

II.II: Chrzazvez et al. 2014.

When compared with Chrzazvez et al. (2014), the results are roughly similar, albeit with some important differences, explainable by different burning temperatures (400°C v 350°C). Chrzazvez studied interspecific differences in mechanical strength and fragmentation under pressure as charcoal's primary taphonomic change, but also noted mass loss in whole charcoal cubes identically-sized to my samples. Overall different percentages can be explained by different burning temperatures and experimental procedures, as Chrzazvez used foil and sand to exclude oxygen, whilst I used foil alone, which explains their higher charcoal production values – however the relative differences compared to pine production are similar, with their relative conversion rates (compared with *Pinus* = 1) falling within my standard error margins for *Carpinus* and *Populus*, and very nearly for *Acer*. The outlier is *Fagus*, as I produced far less *Fagus* and *Fraxinus* charcoal than Chrzazvez (my results are minimally affected however, as only one site contains *Fagus*). Chrzazvez' results cluster proportionally closer to *Pinus* values than mine, showing only a 0.2 (20%) maximum difference compared to my 0.3392 (33%) difference. There is some consistency in low-high orderings of genera by production ($R^2 = 0.1878$, $p = 0.2440$), but this is not as significant as with Feurdean's study.

Table 7.5: Comparing Chrzazvez' (2014) and my (2023) findings. This is also presented in Graph A40, p.406.

Chrzazvez' findings (400°C) – Genus and conversion rate (%)		**Relative Conversion (compared to *Pinus* = 1)**	**My findings (350°C) – Genus and conversion rate (%)**		**Relative Conversion (compared to *Pinus* = 1)**
Carpinus	30%	0.8000	*Fagus*	22.84%	0.6608
Betula	31%	0.8267	*Betula*	25.47%	0.7368
Corylus	32%	0.8533	*Carpinus*	26.76%	0.7740
Populus	32%	0.8533	*Corylus*	27.25%	0.7882
Acer	32%	0.8533	*Fraxinus*	27.34%	0.7910
Fagus	34%	0.9067	*Quercus*	27.62%	0.7991
Quercus	37%	0.9867	*Acer*	27.94%	0.8083
Pinus	37.5%	1.00	*Populus*	30.59%	0.8850
Fraxinus	40%	1.0667	*Pinus*	34.57%	1.00

At higher temperature burnings, differences between studies further increase, with no relative conversion rates comparing at all accurately, almost random low-high orderings of genera ($R^2 = 0.03361$, $p = 0.6368$), and only *Fraxinus*' relative conversion rates falling within my standard error margins. This is quite possibly due to their protocol of utilizing both aluminium foil and sand, which further exclude oxygen, and also keep the samples together and prevent loss, which occurred in my samples. My methodology better represents real-life fires, which are not contained, and must undergo recovery procedures causing loss, as my procedure did.

Table 7.6: Comparing my higher-temperature burnings with Chrzazvez (2014). This is also presented in Graph A41, p.406.

Chrzazvez' findings (750°C) – Genus and conversion rate (%)		**Relative Conversion (compared to *Pinus* = 1)**	**My findings (700°C) – Genus and conversion rate (%)**		**Relative Conversion (compared to *Pinus* = 1)**
Betula	16%	0.8421	*Fraxinus*	0.393%	0.6764
Corylus	17%	0.8947	*Pinus*	0.581%	1.00
Populus	17%	0.8947	*Corylus*	1.28%	2.2031
Fraxinus	18%	0.9474	*Fagus*	1.384%	2.3821
Carpinus	18%	0.9474	*Acer*	1.444%	2.4854
Pinus	19%	1.00	*Populus*	1.476%	2.5404
Fagus	19%	1.00	*Betula*	1.722%	2.9639
Acer	19%	1.00	*Carpinus*	1.871%	3.2203
Quercus	19%	1.00	*Quercus*	1.9185%	3.3021

II.III: Feurdean 2021.

Feurdean (2021) studied *Pinus, Picea* and Betula at several temperatures, including 350°C, in a similar muffle furnace. However, Feurdean studied smaller barked twigs, only limiting oxygen intake through the crucible lid, rather than using closer-wrapped aluminium foil. The conversion rates here are very different due to these two practices, with no relative conversion rates falling within my standard error margins.

Table 7.7: Comparing Feurdean's (2021) and my (2023) findings.

Feurdean's findings (350°C) – Genus and conversion rate (%)		**Relative Conversion (compared to *Pinus* = 1)**	**My findings (350°C) – Genus and conversion rate (%)**		**Relative Conversion (compared to *Pinus* = 1)**
Pinus	8.35	1.00	*Betula*	25.469	0.7368
Betula	10.9	1.3054	*Picea*	34.3	0.9922
Picea	16.8	2.0120	*Pinus*	34.568	1.00

II.IV: Rossen and Olson (1985).

Rossen and Olson (1985) studied North American wood-to-charcoal conversion rates, at a very similar temperature to mine (330°C), excluding oxygen with sand. Both sets emphasise conifers' and *Castanea*'s high charcoal production. Their use of American-specific rather than European-specific species within each genera, explains differences between lower-producing genera. Additionally Rossen and Olson's study has a wider range of conversion values than mine, although of all the studies, it represents the closest overall conversion rate values; as expected given the similar experimental designs. For actual conversion rates, their *Celtis* value falls within my standard error range, and their *Populus* is near it; for relative conversion rates compared to *Pinus* = 1, *Juglans* and *Castanea* fall within my standard error ranges, and *Acer, Celtis* and *Populus* are near it. Notably however, relative low-high orderings of genera by charcoal production between our studies shows significant correlations (R^2 = 0.4526, p = 0.0330).

Table 7.8: Comparing Rossen and Olson's (1985) and my (2023) findings. This is also presented in Graph A42, p.407.

Rossen and Olson's findings (330°C) – Genus and conversion rate (%)		**Relative Conversion (compared to *Pinus* = 1)**	**My findings (350°C) – Genus and conversion rate (%)**		**Relative Conversion (compared to *Pinus* = 1)**
Acer	23.50	0.7475	*Quercus (deciduous)*	26.035	0.7532
Juglans	25.61	0.8146	*Fraxinus*	27.3425	0.7910
Celtis	27.66	0.8798	*Acer*	27.94	0.8083
Fraxinus	28.78	0.9154	*Celtis*	28.029	0.8108
Populus	29.30	0.9319	*Juglans*	28.347	0.8200
Quercus (deciduous)	31.44	1.00	*Ulmus*	30.045	0.8692
Pinus	31.44	1.00	*Populus*	30.591	0.8850
Ulmus	32.79	1.0429	*Pinus*	34.568	1.00
Castanea	34.18	1.0872	*Juniperus*	35.599	1.0298
Juniperus	42.49	1.3515	*Castanea*	37.376	1.0812

II.V: Thery-Parisot et al. 2014.

Thery-Parisot and her team principally studied charcoal degradation into size classes instead of conversion rates. Thus their study better represents my second set of experiments than my first; however it usefully outlines what may be found in the archaeological record upon recovery, rather than the charcoal entering the ground. Their study is on live hearths composed of the different genera, and thus, whilst more realistic, experienced much higher variability than charring in muffle furnaces. The top temperatures recorded varied from fire to fire, but varied from c.710-920°C. The primary difference of course is that, in open-fire conditions, the wood was not burnt in specifically reducing environments, and thus specific fire conditions and wood size calibre was far more important than in my experiment. This study is most disparate from my own, with almost random distributions compared to mine, random low-high orderings of genera ($R^2 = 0.01148$, $p = 0.8192$), and with no relative conversion rates falling within my standard errors. The only agreement is that *Betula* and *Carpinus* in both samples had higher conversion rates than *Pinus*. However, had their study only looked at conversion rates rather than rates of production in specific size ranges, then the two studies may have found more similar results.

Table 7.9: Comparing Thery-Parisot's (2014) and my (2023) findings. This is also presented in Graph A43, p.407.

Thery-Parisot et al.'s findings (710-920°C) – Genus and proportion of >2mm charcoal fragments		**Relative Conversion (compared to *Pinus* = 1)**	**My findings (700°C) – Genus and conversion rate (%)**		**Relative Conversion (compared to *Pinus* = 1)**
Populus	1.5	0.5837	*Pinus*	0.581	1.00
Quercus (deciduous)	1.6	0.6226	*Corylus*	1.28	2.2031
Olea	2.05	0.7977	*Populus*	1.476	2.5404
Pinus	2.57	1.00	*Quercus (deciduous)*	1.517	2.6110
Betula	2.8	1.0895	*Betula*	1.722	2.9639
Corylus	3.55	1.3813	*Carpinus*	1.871	3.2203
Carpinus	3.85	1.4981	*Olea*	2.271	3.9088

II.VI: Hudspith et al. 2018.

Finally, Hudspith et al. (2018) studied differential charcoal production through very different methods. Instead of wood samples measured by mass, Hudspith instead burnt organic litter (leaves and stems) with a radiating heat flux of 50kW/m^2 instead of a set temperature. They measured by volume instead of mass for initial input, although recording different masses and varying sample densities, and burning under reduced oxygen conditions. Of their studied genera, only *Pinus* (in their case *P. radiata*), *Buxus* and *Laurus* overlap with my studied genera. Their findings greatly differ from mine, especially regarding *Laurus'* conversion rate. No relative conversion rates fall within my standard error margins. This is due to different experimental methodologies, and by our burning different parts of the plant under different burning and reduction conditions. The overall extremely low conversion rates of all genera (mine being c.100x higher for *Laurus* and *Buxus*) result from them utilizing plant parts which produce little charcoal, and which may also create it in different proportions to wood alone.

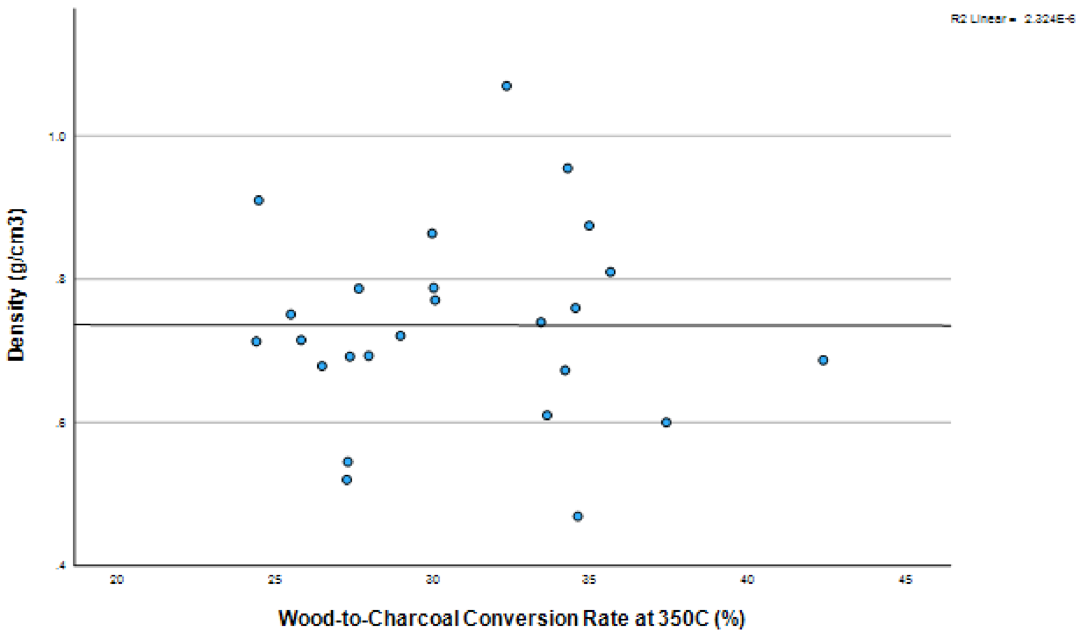
Table 7.10: Comparing Hudspith's (2018) and my (2023) findings.

Hudspith's findings – Genus and Char Mass Fraction		**Relative Conversion (compared to *Pinus* = 1)**	**My findings (350°C) – Genus and conversion rate (%)**		**Relative Conversion (compared to *Pinus* = 1)**
Laurus	0.03	0.2609	*Buxus*	32.31	0.9367
Buxus	0.06	0.5217	*Pinus*	34.568	1.00
Pinus	0.115	1.00	*Laurus*	34.887	1.009

Wood-to-charcoal conversion rates, when differing under identical environmental conditions, must result from different innate qualities of woods themselves. When discussing commercial charcoal burning in Africa and differing charcoal rates within a genus, Mlaouhi says that "the yields of charcoal are relative to the wood density" (Mlaouhi et al. 1999, p.1121). However, Graph 7.1 below shows no correlation between density and conversion rate. Denser woods could create proportionally more charcoal, as fewer oxygen-filled interstices create oxidizing environments; or they might create less charcoal if the spaces were instead filled with water or burnable substances (e.g. resin) which were more prone to being lost. The lack of correlation here suggests that density may be less important than the wood's chemical composition. Wood density values are below in Table 7.11, as means calculated from multiple papers (all cited).

Table 7.11: Density values for my studied genera. These are taken from published literature (all cited) and from a range of species within each genus. These values therefore represent an average for the entire engine, but not necessarily for the particular species burnt. I thought this more appropriate, as the species I burnt is in itself only an example, and the genus found in the charcoal record will not always be this species.

Genus	Density (g/cm^3)	Mean	References
Acer	0.38, 0.57, 0.6, 0.63, 0.7, 0.72, 0.79, 0.81, 0.84, 0.89	0.693	Bhatt and Todaria 1992, 1993, Jain and Singh 1999, Lingens et al. 2005, Nunez-Reguiera et al. 1997, Savi et al. 2018
Alnus	0.316, 0.354, 0.43, 0.495, 0.513, 0.625, 1.08	0.545	Bhatt and Todaria 1993, Bishop et al. 2015, Kataki and Konwer 2001, Moya and Tenorio 2013, Senelwa and Sims 1999
Arbutus	0.61, 0.76, 0.77	0.713	Barboutis and Philippou 2005, Dimitrakopous and Panov 2001
Betula	0.56, 0.673, 0.76, 0.77, 0.801, 0.84, 0.85	0.751	Bhatt and Todaria 1992, 1993, Bishop et al. 2015, Jain and Singh 1999, Nunez-Reguiera et al. 1997
Buxus	1.07	1.07	Bhatt and Todaria 1993
Castanea	0.59, 0.61	0.6	Di Blasi et al. 2001, Nunez-Reguiera et al. 1997
Corylus	0.52	0.52	Savi et al. 2018
Erica	0.76	0.76	Barboutis and Philippou 2005
Fraxinus	0.43, 0.63, 0.689, 0.79, 0.801, 0.81	0.692	Bhatt and Todaria 1993, Bishop et al. 2015, Nunez-Reguiera et al. 1997, Savi et al. 2018
Hippophae	0.61	0.61	Bhatt and Todaria 1992
Ilex	0.86, 0.96	0.91	Bhatt and Todaria 1992, 1993
Juniperus	0.8, 0.82	0.81	Bhatt and Todaria 1992, 1993
Olea	0.49, 0.71, 0.74, 0.92	0.715	Bhatt and Todaria 1993, Kebede and Soromessa 2018
Phillyrea	0.84, 0.91	0.875	Barboutis and Philippou 2005, Savi et al. 2018
Pinus	0.282, 0.292, 0.39, 0.45, 0.46, 0.49, 0.508, 0.513, 0.54, 0.61, 0.625	0.469	Bhatt and Todaria 1992, 1993, Bishop et al. 2015, Di Blasi et al. 2001, Kataki and Konwer 2001, Lingens et al. 2005, Senelwa and Sims 1999, Tran and White 1992
Pistacia	0.67, 0.71, 0.72, 0.76, 1.08	0.788	Dimitrakopoulos and Panov 2001, Savi et al. 2017
Prunus	0.625, 0.633, 0.66, 0.753, 0.79, 0.84, 0.88	0.74	Bhatt and Todaria 1993, Bishop et al. 2015, Jain and Singh 1999, Kataki and Konwer 2001, Nunez-Reguiera et al. 1997, Savi et al. 2018
Quercus	0.55, 0.62, 0.64, 0.65, 0.66, 0.689, 0.72, 0.74, 0.76, 0.78, 0.8, 0.81, 0.831, 0.833, 0.842, 0.88, 0.93, 0.95, 1, 1.053	0.787	Barboutis and Philippou 2005, Bhatt and Todaria 1993, Bishop et al. 2015, Dimitrakopoulos and Panov 2001, Jain and Singh 1999, Kataki and Konwer 2001, Lingens et al. 2005, Meetei et al. 2015, Nunez-Reguiera et al. 1997, Savi et al. 2018, Sousa et al. 2018, Tran and White 1992
Rhamnus	0.83, 1.08	0.955	Bhatt and Todaria 1993
Salix	0.5, 0.62, 0.71, 0.715, 0.72, 0.81	0.679	Bhatt and Todaria 1992, 1993, Kataki and Konwer 2001, Nunez-Reguiera et al. 1997
Sorbus	0.75, 0.83, 0.86, 0.929, 0.95	0.864	Bhatt and Todaria 1993, Bishop et al. 2015, Korkut and Budakci 2010, Nunez-Reguiera et al. 1997, Savi et al. 2018
Tamarix	0.66, 0.686	0.673	Sadegh et al. 2012
Taxus	0.65, 0.67, 0.74	0.687	Bhatt and Todaria 1992, 1993, Nunez-Reguiera et al. 1997
Ulmus	0.609, 0.753, 0.95	0.771	Bhatt and Todaria 1993, Bishop et al. 2015
Viburnum	0.47, 0.725, 0.81, 0.88	0.721	Bhatt and Todaria 1992, 1993, Kataki and Konwer 2001



Graph 7.1: A comparison of Density (calculated from literature, p.187) and Wood-to-Charcoal Conversion Rates at 350C (own dataset, p.175) showing a complete lack of correlation, when a positive correlation would be expected (R2 = 2.324e-6).

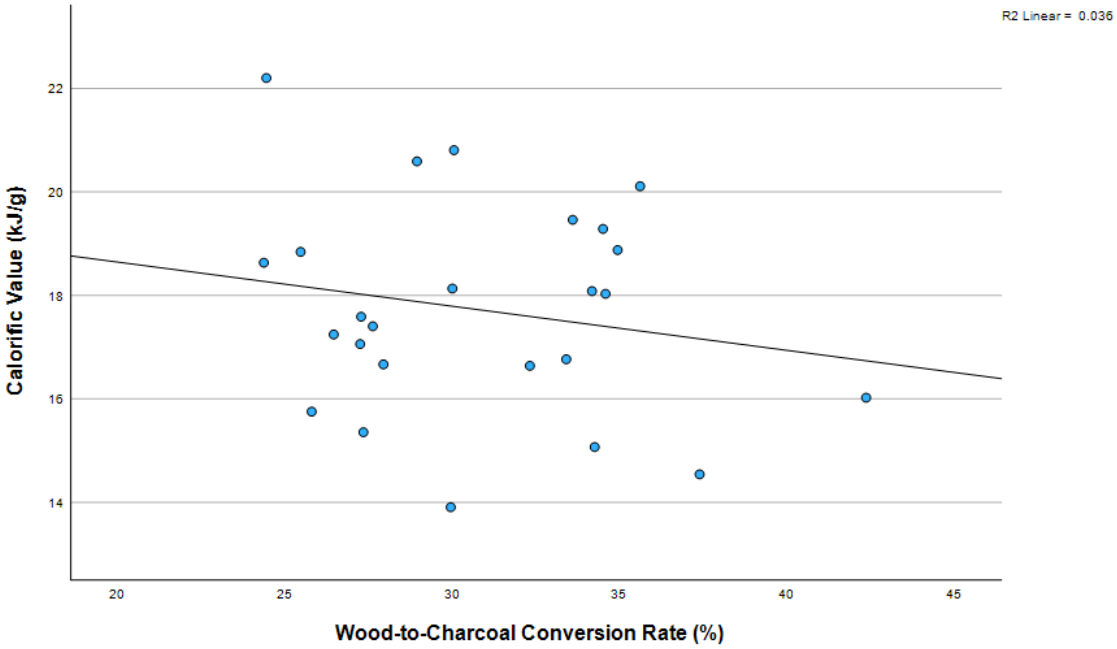
Graph 7.2 (below) shows minimal correlation between calorific value (for the specific species studied, rather than the genera) and species conversion rate. A negative correlation would be expected, as higher calorific values mean more energy released, and unless certain woody pyrolyzing compounds are particularly more energy-rich than others, more energy released indicates more fuel was burnt, with less remaining as charcoal. However, this is not the case. Likewise, conversion rates and ash contents do not correlate (Graph 7.3, below, R2 = 0.009). Theoretical anti-correlations of charcoal and ash production do not appear here. This phenomenon is as yet unexplained, and may just be due to variability in noting ash production, as bark produces much more ash than wood, which biases certain samples. Calorific Value and Ash Contents for the various genera can be found below in Tables 7.12 and 7.13; as with density values, they are calculated as means from various different papers (all cited).

Table 7.12: Calorific values for my studied genera. As with Table 7.11 above, the mean calorific values represent an average across the whole genus rather than for a particular species within it.

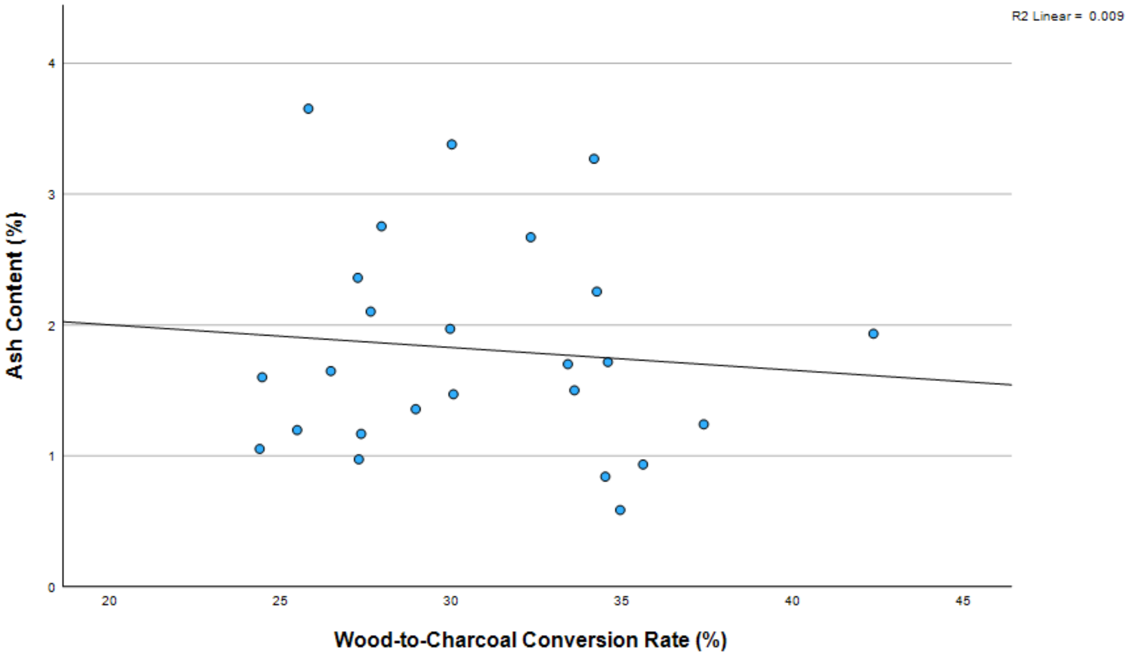
Genus	Calorific Values (kJ/g)	Mean	References
Acer	5.053, 8.747, 15.615, 17.1, 17.38, 17.795, 18.436, 18.5, 18.637, 21.2, 24.87	16.667	Bhatt and Todaria 1992, 1993, Bjorn et al. 2012, Jain and Singh 1999, Nunez-Regueira et al. 1996, Telmo and Lousada 2011
Alnus	4.018, 15.09, 15.29, 18.995, 19.8, 20.94, 21.072, 25.5	17.588	Bhatt and Todaria 1993, Hughes 1971, Kataki and Konwer 2001, Moya and Tenorio 2013, Nunez-Regueira et al. 1997, Senelwa and Sims 1999
Arbutus	17.322, 18.24, 19.07, 19.11, 19.412	18.631	Barboutis and Lykidis 2014, Barmpoutis et al. 2015, Dimitrakopoulos and Panov 2001, Martinez-Perez et al. 2015, Siafaca et al. 1980
Betula	6.53, 16.6, 17.9, 19.11, 19.65, 19.761, 21.072, 21.522, 22.3, 23.966	18.841	Bhatt and Todaria 1992, Bjorn et al. 2012, Hughes 1971, Geyer et al. 1987, Jain and Singh 1999, Nunez-Regueira et al. 1997
Buxus	16.64	16.64	Bhatt and Todaria 1993
Castanea	5.363, 8.515, 15.468, 17.130, 17.92, 18.653, 18.754	14.543	Monarca et al. 2011, Nunez-Regueira et al. 1996, Telmo and Lousada 2011
Corylus	16.45, 17.67	17.06	Monarca et al. 2011
Erica	18.63, 19.343, 19.878	19.284	Barboutis and Lykidis 2014, Barmpoutis et al. 2015, Carrion-Prieto et al. 2017, Dimitrakopoulos and Panov 2001
Fraxinus	3.642, 15.69, 16.259, 16.45, 17.07, 19.09, 19.29	15.356	Bhatt and Todaria 1993, Geyer et al. 1987, Monarca et al. 2011, Nunez-Regueira et al. 1997, Telmo and Lousada 2011
Hippophae	18.9, 20.02	19.46	Bhatt and Todaria 1992, Raichal 2009
Ilex	22.2	22.2	Bhatt and Todaria 1992
Juniperus	18.523, 19.004, 22.8	20.109	Bhatt and Todaria 1992, Siafaca et al. 1980
Olea	13.354, 15.3, 15.7, 16.861, 17.556	15.754	Bhatt and Todaria 1993, Velazquez-Marti et al. 2017, Siafaca et al. 1980
Phillyrea	18.577, 19.175	18.876	Barboutis and Lykidis 2014, Barmpoutis et al. 2015, Siafaca et al. 1980
Pinus	5.868, 7.646, 16.81, 16.935, 17.5, 17.8, 17.85, 18.113, 18.68, 18.7, 18.86, 18.9, 19.238, 19.3, 19.48, 20, 20.237, 20.5, 20.658, 22, 23.56	18.03	Aniszewska and Gendek 2014, Bhatt and Todaria 1992, 1993, Dimitrakopoulos and Panov 2001, Jain 1992, Kataki and Konwer 2001, Munalula and Meincken 2009, Nielsen et al. 2011, Nunez-Regueira et al. 1996, Senelwa and Sims 1999, Siafaca et al. 1980, Susott 1980, Telmo and Lousada 2011
Pistacia	17.347, 18.916	18.132	Dimitrakopoulos and Panov 2001, Siafaca et al. 1980
Prunus	5.565, 13.744, 15.552, 16.02, 17.458, 18.256, 19.34, 19.6, 20.061, 22.06	16.766	Bhatt and Todaria 1993, Jain and Singh 1999, Kataki and Konwer 2001, Nunez-Regueira et al. 1997, Telmo and Lousada 2011, Velazquez-Marti et al. 2017
Quercus	4.297, 7.794, 15.361, 15.74, 17.468, 17.61, 17.98, 18.01, 18.041, 18.12, 18.541, 18.582, 18.636, 18.69, 18.696, 19.06, 19.1, 19.17, 19.28, 19.5, 19.568, 23.62	17.403	Barboutis and Lykidis 2014, Barmpoutis et al. 2015, Bhatt and Todaria 1993, Dimitrakopoulos and Panov 2001, Fang et al. 2011, Jain and Singh 1999, Kataki and Konwer 2001, Meetei et al. 2015, Monarca et al. 2011, Nunez-Regueira et al. 1996, Siafaca et al. 1980, Telmo and Lousada 2011
Rhamnus	14.34, 15.8	15.07	Bhatt and Todaria 1993
Salix	6.68, 15.372, 17.4, 18.279, 19.4, 19.7, 19.8, 21.327	17.245	Bhatt and Todaria 1992, 1993, Kataki and Konwer 2001, Nunez-Regueira et al. 1997, Telmo and Lousada 2011
Sorbus	4.520, 16.87, 20.331	13.907	Bhatt and Todaria 1993, Nunez-Regueira et al. 1997
Tamarix	17.11, 17.87, 18.28, 19.07	18.083	Nielsen et al. 2011
Taxus	5.007, 20.561, 22.5	16.023	Bhatt and Todaria 1992, Nunez-Regueira et al. 1997
Ulmus	18.937, 20.28, 23.2	20.806	Bhatt and Todaria 1993, Geyer et al. 1987
Viburnum	18.2, 21.47, 22.1	20.59	Bhatt and Todaria 1992, 1993, Kataki and Konwer 2001

Table 7.13: Ash contents for the studied genera. As with Tables 7.11 and 7.12 above, the ash values represent an average across the whole genus rather than for a particular species within it.

Genus	Ash Content (%)	Mean	References
Acer	1.15, 1.8, 2.1, 4.1, 4.62	2.754	Bhatt and Todaria 1992, 1993, Jain and Singh 1999, Nunez-Reguiera et al. 1997
Alnus	0.24, 0.58, 0.7, 0.97, 1.44, 1.9	0.972	Bhatt and Todaria 1993, Kataki and Konwer 2001, Moya and Tenorio 2013, Nunez-Reguiera et al. 1997, Senelwa and Sims 1999
Arbutus	0.26, 0.52, 0.83, 1.3, 2.35	1.052	Barboutis and Lykidis 2014, Barmpoutis et al. 2015, Dimitrakopoulos and Panov 2001, Martinez-Perez et al. 2015, Siafaca et al. 1980
Betula	0.18, 0.8, 1.2, 1.8, 2	1.196	Bhatt and Todaria 1992, 1993, Jain and Singh 1999, Nunez-Reguiera et al. 1997
Buxus	2.67	2.67	Bhatt and Todaria 1993
Castanea	0.3, 2.18	1.24	Nunez-Reguiera et al. 1997
Corylus	2.36	2.36	Monarca et al. 2011
Erica	0.39, 0.5, 1.63	0.84	Barboutis and Lykidis 2014, Barmpoutis et al. 2015, Carrion-Prieto et al. 2017, Dimitrakopoulos and Panov 2001
Fraxinus	0.8, 0.86, 1.84	1.167	Bhatt and Todaria 1993, Nunez-Reguiera et al. 1997
Hippophae	1.5	1.5	Bhatt and Todaria 1992
Ilex	1.6	1.6	Bhatt and Todaria 1992, 1993
Juniperus	0.6, 0.7, 1.5	0.933	Bhatt and Todaria 1992, 1993, Siafaca et al. 1980
Olea	1, 4.9, 5.06	3.653	Bhatt and Todaria 1993, Siafaca et al. 1980
Phillyrea	0.5, 0.67	0.585	Barboutis and Lykidis 2014, Barmpoutis et al. 2015, Siafaca et al. 1980
Pinus	0.3, 0.45, 0.6, 1.1, 1.5, 1.69, 1.8, 3.3, 4.7	1.716	Bhatt and Todaria 1992, 1993, Dimitrakopoulos and Panov 2001, Jain 1992, Kataki and Konwer 2001, Munalula and Meincken 2009, Nielsen et al. 2011, Siafaca et al. 1980
Pistacia	3.1, 3.66	3.38	Dimitrakopoulos and Panov 2001, Siafaca et al. 1980
Prunus	0.85, 1.5, 1.61, 1.7, 1.84, 2.7	1.7	Bhatt and Todaria 1993, Jain and Singh 1999, Kataki and Konwer 2001, Nunez-Reguiera et al. 1997
Quercus	0.66, 0.85, 1.14, 1.25, 1.6, 1.62, 1.7, 2.4, 2.5, 2.53, 4.25, 4.72	2.102	Barboutis and Lykidis 2014, Barmpoutis et al. 2015, Bhatt and Todaria 1993, Dimitrakopoulos and Panov 2001, Jain and Singh 1999, Kataki and Konwer 2001, Meetei et al. 2015, Nunez-Reguiera et al. 1997, Siafaca et al. 1980
Rhamnus	2.15, 2.36	2.255	Bhatt and Todaria 1993
Salix	0.22, 1.18, 1.6, 2.05, 2.2, 2.63	1.647	Bhatt and Todaria 1992, 1993, Kataki and Konwer 2001, Nunez-Reguiera et al. 1997
Sorbus	0.67, 2.39, 2.85	1.97	Bhatt and Todaria 1993, Nunez-Reguiera et al. 1997
Tamarix	2.99, 3.55	3.27	Nielsen et al. 2011
Taxus	1.72, 1.8, 2.46	1.993	Bhatt and Todaria 1992, 1993, Nunez-Reguiera et al. 1997
Ulmus	0.61, 0.9, 2.9	1.47	Bhatt and Todaria 1993, Geyer et al. 1987
Viburnum	1, 1.2, 1.5, 1.51, 1.57	1.356	Bhatt and Todaria 1992, 1993, Kataki and Konwer 2001



Graph 7.2: A similar lack of correlation between Calorific Value (calculated from literature, p.189) and Wood-to-Charcoal conversion rates at 350C (own data, p.175), when a negative correlation would be expected (R2 = 0.036).



Graph 7.3: A similar lack of correlation between Ash Content (calculated from literature, p.190) and Wood-to-Charcoal conversion rates at 350C (own data, p.175), when a negative correlation would be expected. The R2 value is especially low (0.009).

III: Fragmentation Rate Experimental Results.

This experiment took place exclusively on charcoal samples without surface fissures or other mechanical flaws. I used 10 cubed samples from each genus: creating more charcoal for certain genera (e.g. *Castanea*) to achieve this. If of course a genus usually creates mechanically-unstable charcoal with voids, fissures etc., then this charcoal usually has higher fragmentation rates. Thus my testing with only solid, “pure” charcoal specimens may have ignored important selective aspects of the process. However, creating solid charcoal depends not only on the genus’ chemical properties, but also its state of decay, moisture content, and perhaps most importantly, random combustion processes, including proximity to other samples and any sudden heat fluctuations. These variables cannot be considered here.

When crushed, the charcoal varied between two extremes. At one end, vitrified charcoal broke into larger, irregular lumps with shiny, multifaceted faces more resembling glass than charcoal, and following similar fracture patterns. This was particularly noticeable in *Taxus*, and may have been a byproduct of resin combustion here. At the other end, highly dry, crumbly and powdery charcoal formed charcoal fibres with large length-to-width ratios. However, these were also the most friable, crumbling during extraction and sorting processes. Vitrified charcoal would probably fragment the least, and it is unknown whether vitrification hinders identification. Crumbling charcoal on the other hand would have become most waterlogged, not surviving flotation/sorting, and would often form pieces too small to identify. The results presented below in Table 7.14 show the numbers, masses and ratios of various fragmentation patterns observed in this experiment.

Table 7.14: Comparing fragmentation patterns of all the tested genera (excluding Celtis, Phillyrea and Pistacia). An asterisk by the genus name indicates that nothing was lost through the smallest (1mm) sieve.

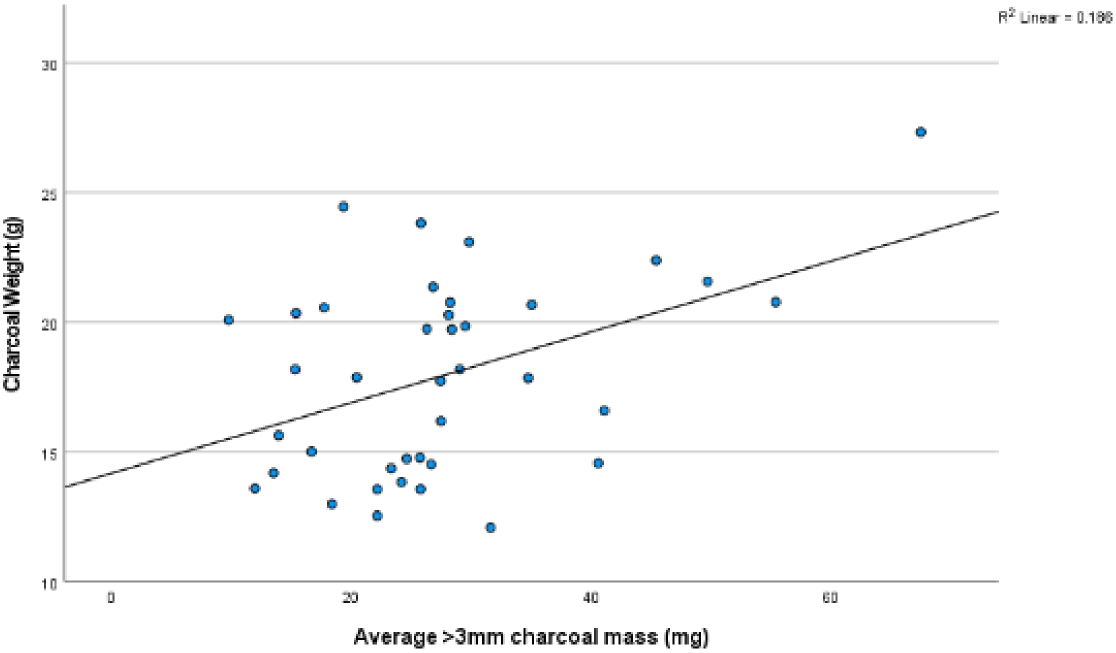
Genus	**Number of fragments >6mm/3-6mm (total)**	**Number of fragments >6mm/3-6mm (total) ratioed to an input charcoal mass of 1g**	**Average Mass per fragment >3mm (mg)**	**Ratio of Number of Fragments >6mm to those 3-6mm**	**% Mass remaining >1mm**	**% Mass remaining >3mm**
Acer	140/472 (612)	7.1/23.9 (31)	28.37	1 : 3.37	98.39%	88.07%
Alnus	154/612 (766)	10.3/40.8 (51.1)	16.68	1 : 3.97	95.89%	85.19%
Amygdalus	149/428 (577)	8.4/24.1 (32.6)	27.43	1 : 2.87	99.48%	89.27%
Arbutus	103/600 (703)	7.3/42.3 (49.6)	13.52	1 : 5.83	88.00%	67.04%
Betula	123/381 (504)	8.6/26.5 (35.1)	23.32	1 : 3.10	95.24%	81.89%
*Buxus**	141/348 (489)	6.3/15.6 (21.9)	45.4	1 : 2.47	100%	94.47%
*Carpinus**	118/262 (380)	5.7/12.6 (18.3)	55.37	1 : 2.22	100%	95.95%
Castanea	12/323 (335)	0.6/16.1 (16.7)	9.78	1 : 26.92	41.27%	16.32%
Cornus	133/474 (607)	10.2/36.5 (46.8)	18.38	1 : 3.56	96.08%	85.95%
*Corylus**	135/434 (569)	9.2/29.5 (38.6)	24.61	1 : 3.21	100%	92.94%
Crataegus	145/500 (645)	7.3/25.3 (32.7)	26.28	1 : 3.45	95.97%	85.92%
*Cytisus**	139/418 (557)	8.6/25.8 (34.4)	27.47	1 : 3.01	100%	91.4%
*Erica**	91/263 (354)	7.5/21.8 (29.3)	31.6	1 : 2.89	100%	92.47%
*Fagus**	164/445 (609)	8.3/22.3 (30.7)	29.5	1 : 2.71	100%	90.21%
Ficus	178/785 (963)	13.1/57.8 (70.9)	11.96	1 : 4.41	96.77%	84.85%
Fraxinus	122/340 (462)	8.4/23.4 (31.9)	26.66	1 : 2.79	97.66%	84.93%
*Hedera**	111/241 (352)	7.6/16.6 (24.2)	40.58	1 : 2.17	100%	98.12%
*Hippophae**	165/413 (578)	8/20 (28)	35.03	1 : 2.50	100%	93.72%
*Ilex**	132/410 (542)	8.9/27.8 (36.7)	25.72	1 : 3.11	100%	91.61%
*Juglans**	130/420 (550)	9.4/30.4 (39.8)	24.19	1 : 3.23	100%	92.46%

Genus	**Number of fragments >6mm/3-6mm (total)**	**Number of fragments >6mm/3-6mm (total) ratioed to an input charcoal mass of 1g**	**Average Mass per fragment >3mm (mg)**	**Ratio of Number of Fragments >6mm to those 3-6mm**	**% Mass remaining >1mm**	**% Mass remaining >3mm**
Juniperus	138/688 (826)	5.6/28.1 (33.8)	19.35	1 : 4.99	84.37%	63.78%
*Larix**	212/649 (861)	8.9/27.2 (36.1)	25.8	1 : 3.06	100%	90.07%
*Laurus**	135/287 (422)	4.9/10.5 (15.4)	67.46	1 : 2.13	100%	97.04%
Olea	187/442 (629)	9.2/21.8 (31)	28.1	1 : 2.36	97.27%	87.2%
Picea	146/341 (487)	10.8/25.2 (35.9)	25.77	1 : 2.34	99.67%	92.62%
Pinus	111/620 (731)	6.1/34.1 (40.2)	15.33	1 : 5.59	84.47%	61.69%
Populus	160/358 (518)	12.8/28.6 (41.4)	22.16	1 : 2.24	99.32%	91.64%
Prunus	142/495 (637)	6.7/23.2 (29.8)	26.82	1 : 3.49	94.55%	80.02%
Pyrus	135/503 (638)	6.5/24.2 (30.7)	28.23	1 : 3.73	98.33%	86.78%
Quercus (deciduous)	25/281 (306)	1.2/13.7 (14.9)	17.73	1 : 11.24	50.64%	26.38%
Quercus (evergreen)	44/523 (567)	2.2/25.7 (27.9)	15.39	1 : 11.89	71.16%	42.89%
Rhamnus	88/283 (371)	3.8/12.3 (16.1)	29.82	1 : 3.22	53.12%	47.92%
Salix	129/289 (418)	9.5/21.3 (30.9)	30.48	1 : 2.24	99.99%	94.07%
Sambucus	186/773 (959)	11.9/49.5 (61.4)	13.94	1 : 4.16	98.64%	85.54%
Sorbus	150/610 (760)	8.4/34.2 (42.6)	20.45	1 : 4.07	97.79%	87.03%
*Tamarix**	141/296 (437)	6.5/13.7 (20.3)	49.68	1 : 2.10	100%	95.48%
*Taxus**	58/101 (159)	2.2/3.8 (6)	176.86	1 : 1.74	100%	98.98%
*Ulex**	123/257 (380)	7.4/15.5 (22.9)	41.08	1 : 2.09	100%	94%
Ulmus	129/335 (464)	7.2/18.8 (26)	34.73	1 : 2.60	98.08%	90.34%
*Viburnum**	165/426 (591)	9.1/23.4 (32.5)	29.03	1 : 2.58	100%	91.62%
Mean	**130/428 (558)**	**7.5/24.8 (32.3)**	**31.50**	**1 : 4.14**	**93.30%**	**82.45%**

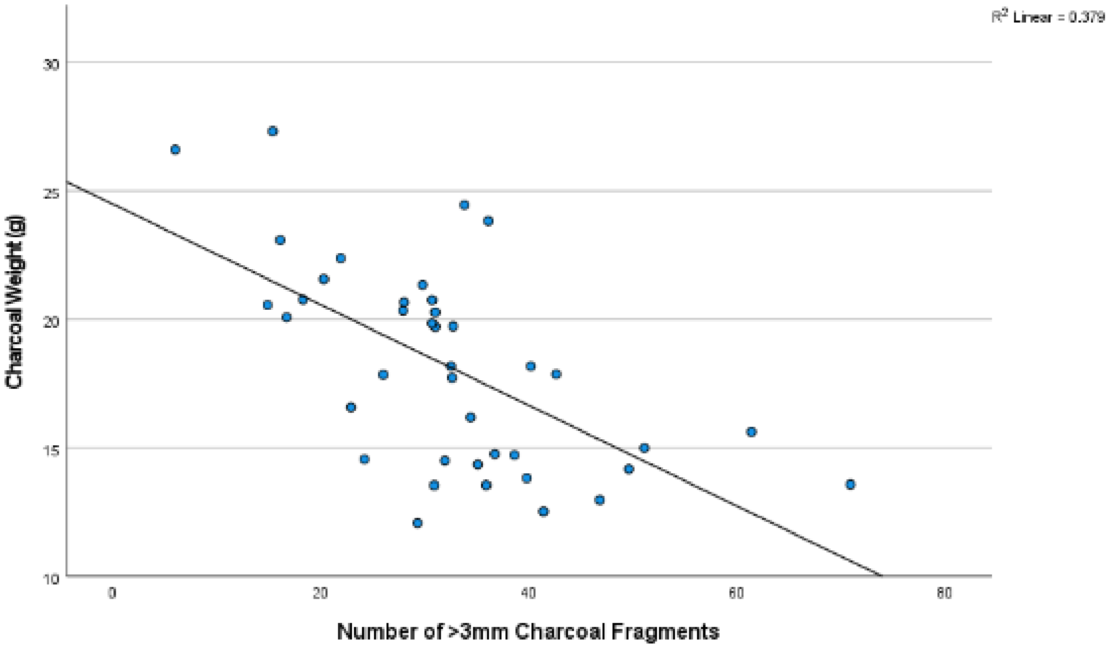
* = all (100%) of the charcoal was over >1mm post-crushing

The number of fragments recovered varied immensely, from 352 (*Hedera*) to 963 (*Ficus*). Likewise, proportions of charcoal lost from the system (>1mm) was often zero, but as high as 58.73% for *Castanea*. However, due to differing densities and small experimental measurement errors, samples had different masses, though similar volumes. Volumetric measurements may be important for fragmentation and recovery, but mass and number of fragments has been consistently used in determining fuel use, attributes and requirements (Belcher et al. 2013, Crawford and Belcher 2020, Halsall et al. 2018). Thus it was necessary to standardize the number of fragments to the output of 1g of charcoal. Because of different wood-to-charcoal conversion rates, this of course translates to different original wood masses.

Higher-mass samples might create different quantities of fragments, and thus bias the samples. If higher masses came from higher densities alone, those samples might be more resistant to crushing pressures, creating fewer fragments. If higher masses came purely from larger volumes however, then larger volumes would create more fragments when crushed, assuming similar resistances to pressure. As it turns out, initial charcoal sample weight had little effect on any factor, possibly because two factors (higher density v larger volume) cancelled each other out. As seen in Appendix Four (Graphs A1-A3), initial charcoal mass did not affect fragment size ratios, percentage of mass falling into Medium and Large size categories, or number of Medium/Large charcoal fragments (unratioed). All of these suggest that minor variations in charcoal mass inputs into this experiment did not impact the results. Initial charcoal masses did somewhat affect the mass of each >3mm fragment (Graph 7.4, $R^2 = 0.186$), where as expected, higher initial masses caused higher fragment masses. Likewise, when initial charcoal weights were compared to the number of fragments (Graph 7.5, $R^2 = 0.379$), when ratioed to 1g of charcoal, there was a negative correlation whereby lower charcoal masses create more fragments. It would have been expected in Graph 7.5 that input charcoal mass and un-ratioed number of fragments would roughly correlate, as larger masses (assuming larger volumes) theoretically create more fragments, all other factors being equal. The fact that they did not instead suggests that the greater weight of heavier charcoals was caused by higher densities rather than increased volumes, and that these were subsequently also more resistant to crushing and created less fragments than lighter charcoals. When ratioed to standard input masses of 1g of charcoal in Graph 7.5, a negative correlation resulted, further suggesting that smaller charcoal mass input values (resulting from less dense charcoals) create more fragments.



Graph 7.4: The weak correlation between the initial mass of charcoal crushed in this experiment (for each genus) and the average mass of each charcoal fragment over 3mm. The weakness of this correlation is caused by the variable amounts of fragments produced by each genus under standard crushing conditions (R2 = 0.186).



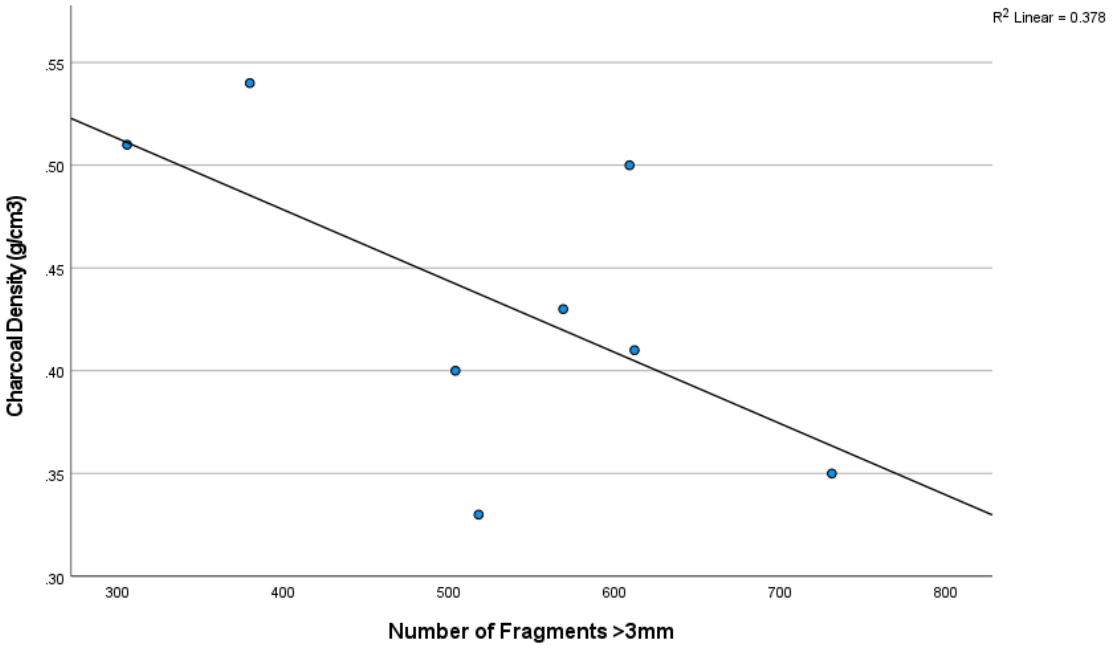
Graph 7.5: The weak anticorrelation between the initial mass of charcoal crushed in this experiment (for each genus) and the combined number of Medium and Large charcoal fragments produced, when ratioed to a standard mass of 1g charcoal being crushed (R2 = 0.379).

It might likewise be expected that charcoal density would determine fragmentation rates. The expected hypothesis is that denser charcoals would resist crushing better than less dense ones; therefore denser charcoals, when crushed, would form fewer, larger fragments with higher masses (both from denser charcoal being heavier and from there being fewer fragments), therefore a larger proportion of fragments and mass in larger size classes. It is always assumed that denser woods create denser charcoals (Assis et al. 2016). However, when correlating *wood density* with the mass of >1mm, 1-3mm and >3mm fractions, fragment size ratios, and fragment numbers (ratioed and unratioed), no correlations appeared (see Appendix Four, Graphs A4-A9). This was unexpected, but suggests that wood density imperfectly translates to charcoal density. Higher density may be caused by more wood fibres in given volumes and fewer air-filled interstices; however these interstices may instead be filled with resin or other flammable substances. Chrzazvez et al. (2014) compared wood density and charcoal density, finding the following:

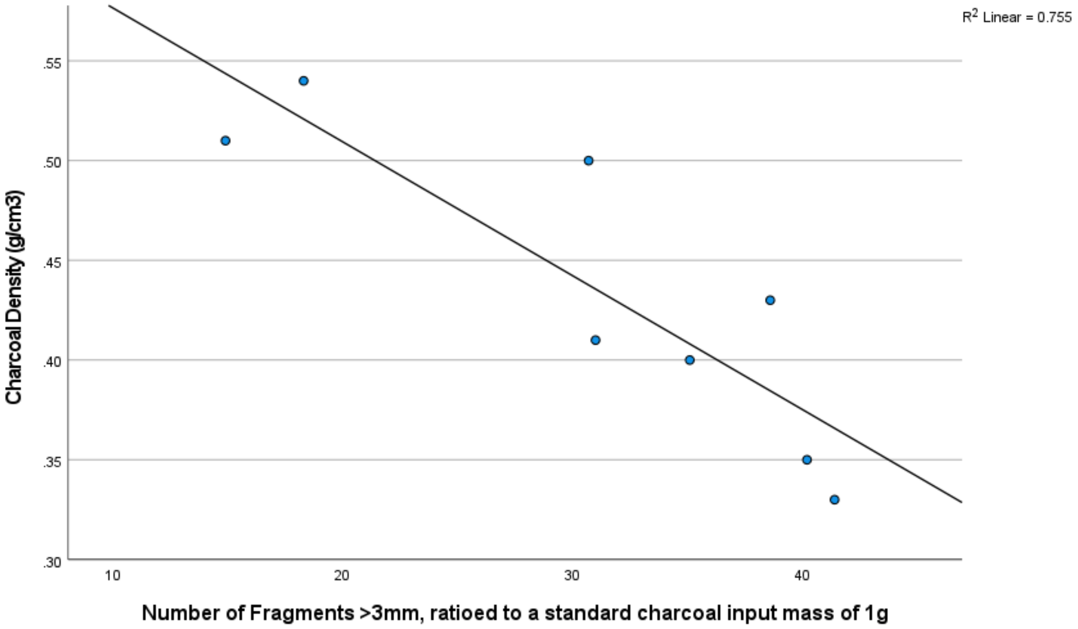
Table 7.15: Chrzazvez et al.'s (2014) results concerning differential wood and charcoal densities.

Genus	**Wood Density (g/cm^3)**	**Charcoal Density (g/cm^3)**	**% Density Loss through Charcoalification**
Carpinus	0.73	0.54	26.03%
Fagus	0.69	0.50	27.54%
Corylus	0.60	0.43	28.33%
Betula	0.59	0.40	32.20%
Populus	0.49	0.33	32.65%
Pinus	0.53	0.35	33.96%
Acer	0.65	0.41	36.92%
Quercus (deciduous)	0.91	0.51	43.96%

It is interesting that the range of values of change of density between wood and charcoal states (26.03-43.96%) are similar to amounts of variation found in different wood-to-charcoal conversion rates (22.84-42.35%). However, these two variables do not correlate at all (Appendix Four: Graph A10). The lack of correlation between wood-to-charcoal conversion rate and density may stem from me averaging densities for each genus, whereas Chrzazvez' team weighed each sample individually. If I use Chrazazvez' charcoal densities, instead of wood densities, I find a weak negative correlation with charcoal density for both raw numbers of >3mm fragments, and even more strongly when this number is ratioed to charcoal input mass = 1g – see Graphs 7.6 and 7.7 beneath.

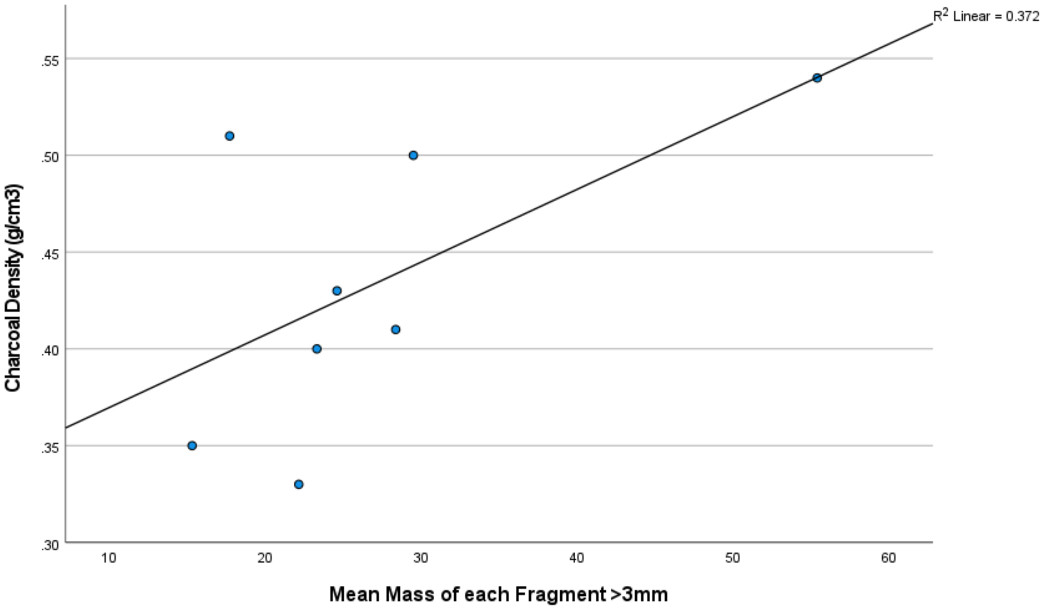


Graph 7.6: The weak negative correlation between charcoal density and the number of fragments produced (R2 = 0.378), as expected given that less dense charcoals are weaker and more prone to splitting into more fragments, compared with equal pressure on denser, stronger charcoals.



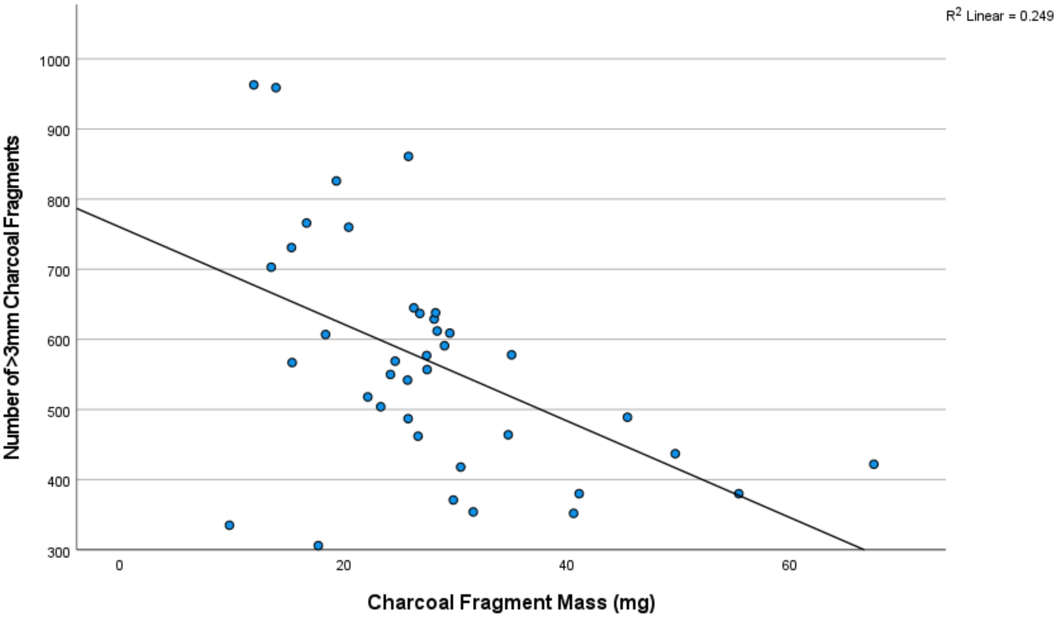
Graph 7.7: The stronger correlation when the number of >3mm fragments is ratioed to a standard input mass (R2 = 0.755). This further confirms that fragmentation depends on charcoal density, but not necessarily on initial wood density.

Additionally, Graph 7.8 below shows another positive correlation between charcoal density and fragment weight. This is expected as denser woods not only split into fewer fragments, so each (larger) fragment will be heavier; but additionally denser woods are innately heavier per given volume. The only uncorrelated variables were charcoal density and proportion by mass remaining >3mm (Appendix Four: Graph A11). Given the proportion remaining in this class show little variation, with differences being the number of fragments and associated weights *within* this size class (see Graph 7.8 below), this was expected. Chrzazvez tested charcoal density on few genera, so I could not test this theory on most of my dataset. Predicted wood-to-charcoal conversion rates (from Experiment 1) correlated only very weakly with number of fragments (Appendix Four: Graph A12), and not at all with fragment size ratios (Appendix Four: Graph A13). Thus fragmentation patterns do not appear to depend straightforwardly on the variables I have considered, although they are still probably based on morphological or mechanical aspects of the wood or charcoal. Further research is required to map correlations between wood density and charcoal density; however, my research indicates that charcoal density correlates with expected levels of charcoal fragmentation.

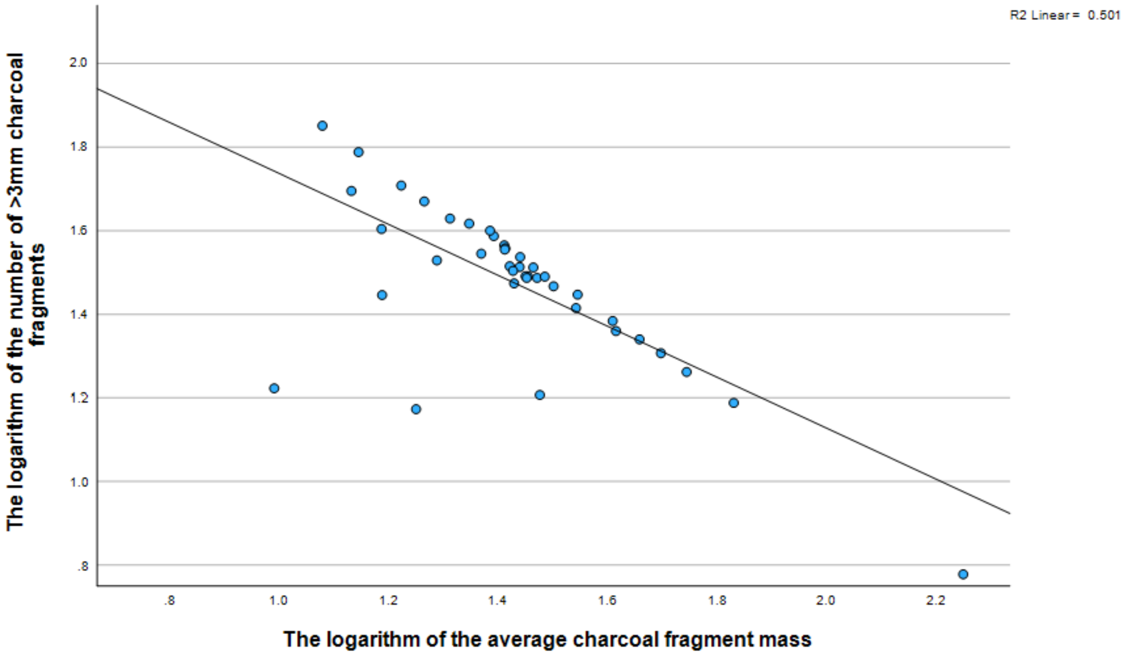


Graph 7.8: A graph showing expected positive correlations between Chrzazvez' (2014) charcoal densities and the mean mass of the Medium and Large fragments in my experiment (R2 = 0.372).

As expected, genera producing more charcoal fragments have lower average fragment masses (>3mm) (Graph 7.9, R2 = 0.249). This trend is increasingly apparent when number of fragments is ratioed to initial charcoal masses being 1g (Graph 7.10, R2 = 0.455). For each genus therefore, fragmentation rates either caused many fragments to be created, which would be recovered via flotation, or fewer larger, heavier fragments which are more obvious for hand-picking. Larger fragments also preserve genera-specific morphological features better, allowing accurate genera-level identification. This suggests that, within the >3mm sample size, all genera preserve the same proportion of original mass for this sample size. This is consistent with the narrow range of high mass percentages preserved in the >3mm fragment fraction, c.85-90%, although there are outliers, to as low as 16% for *Castanea*. Inter-genus variation is therefore not mainly in terms of the mass preserved for each fragment size range, but instead the number of fragments within that range (e.g. >3mm), and the mass of each fragment.



Graph 7.9: the negative correlation between the number of Medium/Large charcoal fragments and the weight of each fragment in this size range. This correlation is entirely expected (R2 = 0.249).



Graph 7.10: the correlation between the number of Medium/Large charcoal fragments and the mass of each fragment in this size group, when ratioed to a standard charcoal input mass of 1g. As the relationship of the respective logarithms of each metric shows a linear relationship, this therefore suggests a reciprocal relationship of $y \infty 1/x$ *for number of fragments and fragment mass, whereby halving the number of fragments doubles each fragment's mass (R2 cubic = 0.455).*

What would have been entirely lost from the system however, <1mm and unable to be identified (see Chapter Seven, p.193)? Three genera (*Castanea, Quercus* and *Rhamnus*) all lost over 20% of their charcoal (by mass) through the 1mm sieve. This implies that regardless of the investigative method and the relative identification bias of large or multiple small charcoal pieces, these three genera would be underrepresented.

If overall number of fragments is the most important criterion for ranking the presence of different genera in the archaeological record, the top five highest number of fragments of charcoal over 3mm (when ratioed to charcoal = 1g) are from *Ficus* (70.9), *Sambucus* (61.4), *Alnus* (51.1), *Arbutus* (49.6) and *Cornus* (46.8), and these genera might be overrepresented. Conversely, the lowest number of fragments >3mm are from *Taxus* (6), *Quercus* deciduous (14.9), *Laurus* (15.4), *Rhamnus* (16.1) and *Castanea* (16.7). The top five fragment producers are uncommon in the Middle Palaeolithic, and it is unlikely that their high fragmentation rate would cause significant bias. Of the low fragment producers, *Quercus* and *Rhamnus* are common, and could be thus underrepresented in current anthracological analysis.

This of course assumes that smaller charcoal, despite having more fragments, is not missed when excavating, and larger charcoal fragments (although having fewer fragments) is more likely to be hand-picked. If mass (positively correlating with predicted size) of fragments is most important for identification, the patterns reverse. *Taxus* (176.86), *Laurus* (67.46), *Carpinus* (55.37), *Tamarix* (49.68) and *Buxus* (45.4) produce largest masses per charcoal fragment (>3mm), but all are rare in Palaeolithic sites. Lowest masses per fragment (>3mm) come from *Castanea* (9.78), *Ficus* (11.96), *Arbutus* (13.52), *Sambucus* (13.94), *Pinus* (15.33) and *Quercus* evergreen (15.39). The latter two are common Neanderthal fuels.

Table 7.16: Comparing fragmentation patterns between Evergreen, Deciduous and Coniferous trees.

Type of Tree	**Number of fragments >6mm/3-6mm (total)**	**Number of fragments >6mm/3-6mm (total) ratioed to a charcoal mass of 1g**	**Average Mass per fragment >3mm (mg)**	**Ratio of Number of Fragments >6mm to those 3-6mm**	**% Mass remaining >1mm**	**% Mass remaining >3mm**
Evergreen	128/416 (544)	7.6/25.3 (32.9)	31.80	1 : 3.81	95.75%	85.57%
Deciduous	130/423 (553)	7.7/24.9 (32.6)	26.96	1 : 4.42	92.10%	81.64%
Conifer	133/480 (613)	6.7/23.7 (30.4)	52.62	1 : 3.54	93.70%	81.43%

Comparing Evergreen, Deciduous and Coniferous trees (Table 7.16, above) shows few differences in any criteria. Conifers have higher >3mm fragment masses, but this is heavily skewed by *Taxus* (176.86mg, 2.6x heavier than the next heaviest genus *Laurus*). All other criteria are very similar; conifers initially have more >3mm fragments than other trees, but once ratioed to 1g charcoal mass, actually have fewer. This suggests that, unlike for wood-to-charcoal conversion rates (Table 7.1, p.175), tree type minimally affects fragmentation rate. This further suggests that fragmentation differences are not due to morphological differences between tree types. If these differences are consistent within a genus, these results are useful for recalibrating existing anthracological diagrams. Given that all current anthracology uses number of charcoal fragments as a proxy for the prevalence of different plants, differential fragmentation is an important bias. I did not count the smallest identifiable charcoal fraction (1-3mm) due to experimental constraints; however those >3mm are listed below in Table 7.17, which is adaptable to any anthracological diagram.

Table 7.17: Number of fragments (>3mm) of all genera as a recalibration tool for existing anthracological diagrams.

Genus	**Number of Fragments >3mm, ratioed to an input charcoal mass of 1g**	**Proportion compared to *Pinus* = 1**
Taxus	6	0.1493
Quercus (deciduous)	14.9	0.3706
Laurus	15.4	0.3831
Rhamnus	16.1	0.4005
Castanea	16.7	0.4154
Carpinus	18.3	0.4552
Tamarix	20.3	0.5050
Quercus (average)	21.4	0.5323
Buxus	21.9	0.5448
Ulex	22.9	0.5697
Hedera	24.2	0.6020
Ulmus	26	0.6468
Quercus (evergreen)	27.9	0.6940
Hippophae	28	0.6965
Erica	29.3	0.7289
Prunus	29.8	0.7413
Fagus	30.7	0.7637
Pyrus	30.7	0.7637
Salix	30.9	0.7687
Acer	31	0.7711
Olea	31	0.7711
Fraxinus	31.9	0.7935
Viburnum	32.5	0.8085
Amygdalus	32.6	0.8109
Crataegus	32.7	0.8134
Juniperus	33.8	0.8408
Cytisus	34.4	0.8557
Betula	35.1	0.8731
Picea	35.9	0.8930
Picea/Larix	36	0.8955
Larix	36.1	0.8980
Salix-Populus	36.2	0.9005
Ilex	36.7	0.9129
Corylus	38.6	0.9602
Juglans	39.8	0.9900
Pinus	40.2	1.0000
Populus	41.4	1.0299
Sorbus	42.6	1.0597
Cornus	46.8	1.1642
Arbutus	49.6	1.2338
Alnus	51.1	1.2711
Sambucus	61.4	1.5274
Ficus	70.9	1.7637

IV: Comparison with Chrzazvez et al. 2014.

This experiment was inspired by Chrzazvez et al. (2014), and follows several similar methodologies; comparisons were therefore essential. Chrzazvez carbonized samples at 400°C as opposed to my 350°C, potentially affecting mechanical properties. They excluded oxygen with foil and sand, as opposed to me using foil alone, and used 4mm, 2mm and 1mm sieve grades, whilst I used 6mm, 3mm and 1mm. Furthermore, they counted the 1-2mm fraction, whereas I did not, using different mechanical methods of crushing to me. In Table 7.18 below (and Graph A44, p.408), where the percentage of charcoal fragments is calculated, it is calculated for Chrzazvez' study where 100% = all charcoal fragments over 2mm are counted, and in mine 100% = all charcoal fragments over 3mm.

Table 7.18: Comparing the ratios of Large and Medium fragments in Chrzazvez et al. (2014) and my own study. This is also presented in Graph A44, p.408.

Chrzazvez' (2014) findings (400°C)		**My findings (350°C)**	
Genus	**% Charcoal Fragments >4mm**	**Genus**	**% Charcoal Fragments >6mm**
Corylus	26.15	*Quercus* (deciduous)	8.17
Acer	27.78	*Pinus*	15.18
Fraxinus	29.85	*Acer*	22.88
Fagus	30.19	*Corylus*	23.73
Carpinus	30.77	*Betula*	24.40
Pinus	31.54	*Fraxinus*	26.41
Betula	33.33	*Fagus*	26.93
Populus	33.33	*Populus*	30.89
Quercus (deciduous)	34.78	*Carpinus*	31.05

The differences between our results highlight how precise sieve grading sizes contribute to proportions of fragments in each size class. Our sets of percentages roughly correlate, with my lower range (22.88-31.05) compared to 26.15-34.78 for Chrzazvez' study, expected for my sieve gradings being 1-2mm larger each time. *Pinus* and *Quercus* however, important Neanderthal woods, both create unusually low proportions of 6mm+ charcoal. This is particularly unexpected for *Quercus*, as it produced the most for Chrzazvez. Although my 3-6mm *Quercus* fragments fell within the range of other genera, albeit near the low end (281 fragments), there were only 25 >6mm fragments, which compared to my mean of 130 >6mm fragments, is extremely low. My testing *Q. petraea*, as opposed to Chrzazvez' testing *Q. pubescens*, might explain this anomaly. This comparison however only compares proportions of fragments in the two highest size categories; other factors such as amount lost (>1mm), fragment weight and overall number of fragments cannot be directly compared.

V: Conclusion.

This experiment has shown that genera-specific differences in 42 wood genera (13 evergreens, 25 deciduous and 5 conifers) strongly affect amounts of charcoal produced. Conversion rates at 350°C range from 22.8% to 42.3% (30.37% mean), and 0.3% to 11.3% at 700°C (3.04% mean). As lab studied, they do not represent actual conversion rates in Neanderthal fires, which would have varied considerably, but conversion rate proportion from genera to genera may still apply in realistic fire settings. Low conversion rates at 700°C suggest that woods experiencing peak temperatures closest to 700°C, would be mostly consumed, leaving minimal charcoal residues. Thus 350°C conversion rates are more important for archaeological recalibrations. However, the 700°C results showed that popular fire-starters (e.g. pine and birch) would not have survived later peak fire temperatures (see p.259), and their archaeological presence indicates them being introduced later in the fire. *Erica*, another useful fire-starter, with much higher 700°C conversion rate of over 7%, could be detected today even if used as a fire-starter. It appears as a Neanderthal fuelwood at Cueva Anton, Cueva del Conde, Gorham's Cave, Klissoura and Riparo Bombrini (Arobba and Caramiello 2009, Carrion et al. 2008, Ntinou 2021, Uzquiano et al. 2008, Zilhao et al. 2016).

My results agree with other similar experiments, although actual conversion rates differ, due to different experimental procedures. Studies by Frejaville et al. (2013) and Rossen and Olson (1985) correlate well with mine; Rossen and Olson's study in particular shows very similar actual conversion rates to mine, as expected from similar experimental designs. Differences when compared to Chrzazvez et al. (2014) are explained by their burning at higher temperatures than me, as genera conversion rate orderings are not preserved with increasing temperature. Some low-producing genera at low temperatures become highly productive at higher temperatures. Hudspith et al. (2018) and Feurdean (2021) both highlight how leaf litter/barked twigs produce less charcoal than larger wood pieces, and Thery-Parisot et al. (2014) highlights how conversion rate and rate of production of charcoal pieces of a given size do not fully tally. When the latter is taken into account, these amounts may change. Even when differences occur however, they all further highlight conifers' higher charcoal production compared to evergreen and deciduous trees.

My second set of experiments, on subsequent taphonomic charcoal fragmentation, shows distinct inter-genera differences. Charcoal fragmentation is important due to number of fragments often being used to measure proportional presence of genera in anthracological diagrams (as opposed to volumetric or mass studies). Under my own conditions (which mimic only certain archaeological trampling events), 1g of charcoal creates 6-71 fragments of identifiable charcoal, each weighing 9.8-

176.9mg. This variation was not between wider tree groups (Deciduous, Evergreen and Coniferous), as with wood-to-charcoal conversion rates, but rather between individual genera. This study of course only explored charcoal fragmentation, and not survival rates of different charcoal size categories, another potential bias. This extreme variation in number of fragments alone though suggests that differential charcoal fragmentation artificially biases inferences about fuel use, if only >3mm charcoals are sampled. If smaller pieces are sampled, this bias reduces, as proportions (by mass) surviving in each size class remains somewhat standardized between genera, and the smaller size range in the 1-3mm class prevents such disparate amounts of fragments being created from a standard mass. Whilst wood density and predicted wood-to-charcoal conversion rates poorly predict potential fragmentation, Chrzazvez et al.'s (2014) *charcoal* densities correlate well with expected fragmentation, with denser charcoals creating fewer, heavier fragments. Once we understand correlations between wood and charcoal densities, the latter can become a proxy for expected fragmentation rates.

Factors behind these varying genera-specific conversion rates remain unexplained. Higher-calorific woods produce less charcoal, but this is only a slight negative correlation; ash content likewise is uncorrelated with charcoal production, surprising given that many studies argue that one is produced at the expense of the other. Density is also uncorrelated with conversion rates, despite limited access to oxygen being an important condition of charcoal production. The answer might be found through chemically analysing the different woods; I believe that high resinous extractive contents cause conifers' high conversion rates, and varying extractive proportions within other trees may correlate with their conversion rates. The value of conversion and fragmentation rates does not however lie in their causes, but rather their effects, and the confusing influences they have on anthracology and attempted environmental and cultural reconstructions. Differential conversion rates affect all charcoal, and differential fragmentation rates affects larger charcoal fragments. Whereas past authors have obviated the effects of differential production and fragmentation on palaeoenvironmental reconstruction, I intend to show that recalibrations taking these into account can significantly change inferred patterns. Furthermore, these inferred patterns directly influence questions of Neanderthal fuel choice. If these biases were 'confusing factors' in a reality dominated by the Principle of Least Effort, then pollen and post-recalibration charcoal values for each genus would become very similar. If this does not happen however, or not consistently across all fuelwood types, then the hypothesis of Neanderthal fuel choice still stands. Recalibrations and discussions of Middle Palaeolithic sites across Europe and the Near East forms the substance of my next chapter.

Chapter Eight: Results applied to Recalibrate Neanderthal Anthracological Diagrams.

As discussed in the previous chapter, recalibration taking differential charcoal creation and differential charcoal fragmentation into account is important for understanding what was actually burnt, rather than what survives today. This in turn is important for understanding both past palaeoenvironments and any fuel selection or optimization. The recalibrations at 350°C and 700°C allow analysis of two different burning phases. Fire-starting woods or those added during its main burning phase, would have experienced higher temperatures closer to 700°C. Experimental wood fires reach c.530-1000°C, and c.700°C represents a mean of these potential temperatures (from Bellomo 1993, Braadbaart et al. 2012, Canti and Linford 2000, March et al. 2014, Sievers and Wadley 2008, Stiner et al. 1995). Thus the latter conversion rates and recalibrations (of 700°C) are more appropriate for fire-starting fuelwoods with low ignition temperatures (for details see Hao et al. 2020, Martinka et al. 2017, Spearpoint and Quintiere 2001). In contrast, only those fuels added occasionally to lower-temperature fires, after peak heat flares, would have experienced optimal wood-to-charcoal conversion temperatures. Many studies find that charcoal production decreases with temperature (Demirbas et al. 2016, Sugumaran and Seshadri 2009, Wilk et al. 2016), however 350°C is an average optimum temperature, and also key as volatile combustion disappears above this temperature (Hu et al. 2021). As lower temperatures produce more charcoal, anthracology is dominated by charcoal from genera added near the end of fires when temperatures are lower, with smaller amounts of those added earlier during high-temperature burning phases. By contrast, as ash and charcoal production rates anticorrelate, ash records are dominated by genera added earlier in fires. It is by comparing and contrasting the two temperatures, and their effects, that we understand the whole process.

The effects of differential charcoal fragmentation, on the other hand, are experienced in some sites more than others due to varying anthropogenic biases. Digs sieving and identifying almost all charcoal (>1mm) experience less genera-specific bias than digs only collecting larger charcoal pieces, as genera-specific fragmentation bias mostly occurs in Medium and Large (>3mm) size fractions. The percentage by mass going into each size fraction remain mostly constant through most of the genera, albeit with exceptions. Furthermore, vastly increased numbers of very small fragments in 1-3mm size ranges, as opposed to >3mm fractions (700+

were regularly found in this Small size range when counted) means that numerically, if smaller fractions were included in analysis, then effects of differential (genera-dependent) fragmentation within larger fractions are masked. Consequently, many sites with very small charcoal pieces are unaffected by this bias.

With these results, I recalibrate the results seen in Chapter Five. Those genera present as pollen and not charcoal are of course excluded from these tables, as they are unchanged by these recalibrations. Additionally, Abric Romani and Cova de Coll Verdaguer exclusively used handpicking to gather their charcoal fragments, as opposed to flotation or wet/dry sieving methods. Although handpicking does not preclude gathering small fragments, its visual recognition system and manual gathering of fragments means that excavators exclusively hand-picking charcoal miss fragments <3mm (Vidal-Matutano 2018, p.16). These two sites, in addition to mass recalibrations, have differential fragmentation recalibration.

Tables 8.1-8.10: Recalibrations of charcoal in the original 10 Middle Palaeolithic Iberian layers at the following sites respectively: El Esquilleu, Cova de Coll Verdaguer, Cueva del Camino, Gorham's Cave and Abric Romani.

8.1: El Esquilleu Level IX-XIII			
Genus	**Original Charcoal %**	**Recalibration for 350°C**	**Recalibration for 700°C**
Betula	9.62	11.76	5.58
Pinus	41.42	37.32	71.20
Sorbus	48.96	50.92	23.22

8.2: El Esquilleu Level XIV-XIX			
Genus	**Original Charcoal %**	**Recalibration for 350°C**	**Recalibration for 700°C**
Betula	1.54	2.07	0.53
Pinus	96.32	95.48	98.86
Sorbus	2.14	2.45	0.61

8.3: El Esquilleu Level XX-XXX			
Genus	**Original Charcoal %**	**Recalibrated for 350°C**	**Recalibrated for 700°C**
Betula	2.38	3.20	0.82
Pinus	97.62	96.80	99.18

8.4: Cova de Coll Verdaguer Unit I				
Genus	**Original Charcoal %**	**Recalibrated for 350°C**	**Recalibrated for 700°C**	**Recalibrated for Fragmentation Bias (and 350°C conversion)**
Pinus	87.10	86.52	95.93	81.34
Prunus	11.91	12.25	3.65	15.54
Quercus (deciduous)	0.99	1.23	0.42	3.12

8.5: Cova de Coll Verdaguer Unit II				
Genus	**Original Charcoal %**	**Recalibrated for 350°C**	**Recalibrated for 700°C**	**Recalibrated for Fragmentation Bias (and 350°C conversion)**
Pinus	94.80	94.63	98.50	92.89
Prunus	5.20	5.37	1.50	7.11

8.6: Cueva del Camino Level V			
Genus	**Original Charcoal %**	**Recalibrated for 350°C**	**Recalibrated for 700°C**
Betula	6.91	9.13	2.45
Fraxinus	0.40	0.49	0.62
Pinus	91.87	89.39	96.59
Quercus (deciduous)	0.40	0.52	0.16
Salix-Populus	0.40	0.47	0.17

8.7: Gorham's Cave Level IV			
Genus	**Original Charcoal %**	**Recalibrated for 350°C**	**Recalibrated for 700°C**
Erica	1.65	1.64	0.14
Juniperus	1.65	1.59	1.23
Olea	2.48	3.30	0.66
Pinus	94.18	93.47	97.97

8.8: Abric Romani Zone V				
Genus	**Original Charcoal %**	**Recalibrated for 350°C**	**Recalibrated for 700°C**	**Recalibrated for Fragmentation Bias (and 350°C conversion)**
Acer	1.81	2.22	0.74	2.82
Hippophae	0.46	0.47	0.79	0.66
Olea	0.46	0.61	0.12	0.77
Pinus	96.82	96.09	98.17	94.13
Quercus (deciduous)	0.46	0.61	0.18	1.61

8.9: Abric Romani Zone IV				
Genus	**Original Charcoal %**	**Recalibrated for 350°C**	**Recalibrated for 700°C**	**Recalibrated for Fragmentation Bias (and 350°C conversion)**
Pinus	99.95	99.93	99.98	99.91
Salix	0.05	0.07	0.02	0.09

8.10: Abric Romani Zone III				
Genus	**Original Charcoal %**	**Recalibrated for 350°C**	**Recalibrated for 700°C**	**Recalibrated for Fragmentation Bias (and 350°C conversion)**
Pinus	99.87	99.87	99.96	99.82
Prunus	0.13	0.13	0.04	0.18

In addition to those already studied, many more Neanderthal sites contain charcoal diagrams without corresponding palynological analysis. I recalibrate anthracological tables from 62 layers in 24 Neanderthal sites – raw data for these recalibrations is presented in Appendix Five. Not all charcoal can be recalibrated in this manner (e.g. that not determined to genus level); percentages of undetermined charcoal vary from 0-81.58% (mean = 18.68%). When further analysis of smaller charcoal fragments or novel methods to better determine charcoal genus become available for these sites, this will enable more accurate understandings of original wood proportions, through further comparing wood charcoal with these additional proxies. Sites where only hand-picked charcoal has been recovered include Abrigo de la Quebrada, Kaldar, Klissoura, Nesher Ramla and Riparo Bombrini. With these sites I also include fragment-bias analysis. Additionally, in several sites only larger size ranges are gathered or analysed. This enables more reliable fragment identification, but has more potential for bias, and these sites are also recalibrated to reflect this. These include Cova Gran, Cueva del Conde, De Nadale, El Salt (excluding Unit Xb) and Klissoura. Because *Celtis, Phillyrea* and *Pistacia* could not to be sampled for fragmentation, when they occur I use average fragment proportions (compared to *Pinus* = 1) of 0.9104. Nowhere do any averaged genera exceed 1.5% of the charcoal sample, mostly remaining under 1%, so using this average does not greatly bias the results. Additionally, in Grotta di Fumane only very large charcoals, over 5mm in size, were gathered, which most closely corresponds to my >6mm size range; thus the recalibration for fragmentation bias for this site is calculated just using relative prevalences of the Large size range in each instance. The total lack of *Rhamnus* and *Laurus* charcoal at 700°C meant that 700°C recalibrations could not be undertaken for Cova Gran S1B-S1F, Cueva del Conde, and

Klissoura Layers XXb-a, XVI-XVII, XII-XIII and IX-X, and La Vina Cave Levls XIIIbas, XIV, XV, I.A. and I.B.

Table 8.11: A list of the sites used in this study.

Site	Age (ka BP)	Mode and Smallest Charcoal Size Recovered (mm)	Reference
Abric del Pastor	75	NF, WS, 0.5	Vidal-Matutano et al. 2015
Abri du Maras	72-91	NF	Moncel et al. 2015
Abrigo de la Quebrada	40.5-82	NF, HP, DS, WS, 0.25	Carrion Marco et al. 2019
Aguilon P5	44.055-49.181	NF, DS, 1	Mazo and Alcolea 2020
Bojnice III	105.1	NF, 2	Valoch and Moncel 2013
Bolomor Cave	160-230	NF, DS, 0.063	Vidal-Matutano et al. 2019
Cova Gran	37.771-43.259	NF, WS, 2	Allue et al. 2018
Cova 120	57.9	NF	Agusti et al. 1991
Cueva Anton	69.1-72.2	WS, 1	Zilhao et al. 2016
Cueva del Conde	37.71-38.25	WS, 2	Uzquiano et al. 2008
De Nadale	70.2	NF, WS, 2	Vidal-Matutano et al. 2022
El Salt	52.3	NF, WS, 2 (Xb = 0.25)	Vidal-Matutano et al. 2018
Grotta di Fumane	36.45-46	NF, WS, HP, 5	Basile et al. 2014
Kaldar Cave	36.75-54.4	NF, WS, HP	Allue et al. 2018
Klissoura Cave	44.8-123.3	NF, WS, HP, 1, 2-4 sampled	Ntinou 2021
La Vina Cave	36	WS, 1.41	De la Rasilla et al. 2020
Llonin Cave	43.539	WS, 1.41	De la Rasilla et al. 2020
Nesher Ramla	80-170	NF, HP	Allue and Zaidner 2022
Les Canalettes	73.5	1	Audiard et al. 2021
Pod Hradem Cave	43-48	NF, WS, 1	Nejman et al. 2018
Riparo Bombrini	42.911-43.087	HP	Arobba and Caramiello 2009
Scladina Cave	130.5	NF, HP	Pirson et al. 2008
Teixoneres Cave	30-90	NF	Lopez-Garcia et al. 2012
Theopetra Cave	57-129	WS, 1	Ntinou and Kyparissi-Apostolika 2016

NF = number of fragments.

WS = wet sieving.

DS = dry sieving.

HP = hand picking.

A large proportion of charcoal is left out of these recalibrations, from it not being calculated to genus level or being left undetermined. Sometimes charcoal are only determined to the clade (Angiospermae, Gymnospermae, Monocotyledoneae, Rosmarinus), family (Cistaceae, Compositae, Ericacea, Euphorbiaceae, Fabaceae/Leguminosae, Labiatae/Lamiaceae, Rosaceae, Ulmaceae), or subfamily (Malaceae, Maloideae/Pomoideae, Prunoideae). Some non-arboreal plants are determined to the genus (*Artemisia, Ephedra, Equisetum, Euonymus, Rosa*); although not main fuels, they could have formed useful firestarting material. Cladistic determinations are too vague to allow insights into the genera used within it; the family however indicates what might have been burnt:

- Cistaceae: rock-roses include low shrubs which could have been expedient firestarting materials. *Cistus ladanifer* contains combustible aromatic resins, and is an ingredient in herbal medicines. This family is found at Abric del Pastor and La Vina.
- Compositae (Asteraceae): daisies contain many subfamilies and genera, ranging from subshrubs to trees, and it is unknown which the Neanderthals may have used. This is only found at Klissoura, almost certainly representing random expedient use, as it is only found in one of fifteen fire-using levels.
- Ericacea: heaths most notably contains *Erica*, a valuable if fast-burning kindling found in many sites. It also contains the arboreal *Arbutus* (most commonly *A. unedo*, the strawberry tree). Ericacea is only found at Abrigo de la Quebrada.
- Euphorbiaceae: spurges contains mostly highly-toxic small shrubs used in traditional medicine. Only found at Abric del Pastor, this could represent random expedient use.
- Fabaceae/Leguminosae: legumes could represent an important Neanderthal food source. As well as edible species, Fabaceae notably contains *Cytisus* and *Ulex*, both found in other Neanderthal fires, as probable firestarters. Fabaceae are found in 11 Neanderthal sites, highlighting their importance to Neanderthal subsistence. Whether these were added as deliberate fire-starters (most likely for broom or gorse) or as byproducts of food foraging is unknown.
- Labiatae/Lamiaceae: sages consists primarily of small herbs, which could have been dietarily important for flavour control, although not as main fuels. It was most likely added as waste disposal of foodsources, at Abric del Pastor and Klissoura.
- Rosaceae: the rose family is the most diverse and important family within the Neanderthal record, containing *Amygdalus, Crataegus, Prunus, Pyrus* and *Sorbus*, which collectively form 8.39% of the charcoal within all my sample sites. In addition to identified genera, other burnable genera within Rosaceae include *Amelanchier,*

Cotoneaster, Cydonia (quince), *Malus* (apple), *Mespilus* (medlar), *Peraphyllum* (wild crab apple) and *Pyracantha*. Additionally, Rosaceae includes many additional edible plants, including *Fragaria* (strawberries) and *Rubus* (blackberries, raspberries). However, Rosaceae is only found at three sites; although Rosaceae subfamilies Malaceae, Maloideae/Pomoideae and Prunoideae are found in eight more.

- Ulmaceae: the elm family most notably contains *Ulmus*, and is found in Abric del Pastor and El Salt. *Ulmus* as a genus is found in five sites.

Certain genera may have been used exclusively as fire-starters; these include *Erica, Hedera* and *Ilex*. Other hypothesized firestarters include *Ephedrae, Equisetum, Euonymus* and *Rosa*. These would have been exposed to the higher 700°C heat in fires, and that conversion rate is most important for determining their abundance. When recalibrated, both prevalences similarly reduce, *Erica* by 86.58% *Hedera* by 87.87%. This suggests that both firestarters may have been much less common than appears from the charcoal. However, this charcoal only takes woody fuel cores into account. This forms most fuelwoods, but many firestarters comprise leaves, needles or bark, which leave fewer charcoal remains. Thus the prevalence of these fire-starters may not be as low as appears from these recalibrations.

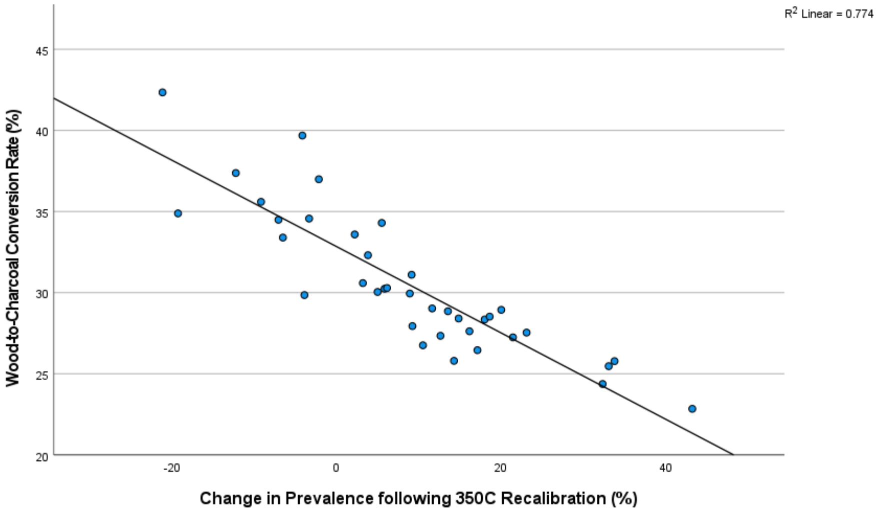
In each instance, amounts by which a genus' prevalence changes is only partly due to its own wood-to-charcoal conversion rate, whereby those with high conversion rates reduce in prevalence through recalibration, and vice-versa for those with low conversion rates. Another factor is of course conversion rates of other genera in the set. For instance, *Sorbus* has the median 300°C conversion rate of 29.95%. In sets including all genera with equal proportions, recalibration would scarcely change its prevalence. However, sites only contain a subsample of genera, and in varying proportions; If *Sorbus* was found alongside genera with only lower conversion rates (e.g. *Betula, Olea, Fraxinus*), it would be the highest producer and thus be recalibrated to a lower prevalence. Alongside genera with higher conversion rates (e.g. *Pinus, Juniperus, Taxus*), conversely it would be the lowest producer and be recalibrated to a higher prevalence. Thus other genera a genus is normally found with are also important. Table 8.12 below demonstrates the mean change in % prevalence in the charcoal record for each genus, as an average of all the sites it occurs in, taking other genera around it into account. This only takes the 350°C recalibrations into account as probably more indicative of most of the charcoal found.

Table 8.12: mean changes in prevalence of the various taxa when 350˚C wood-to-charcoal conversion recalibrations are applied.

Genus	**Changes in Prevalence following 350˚C recalibration (%)**	**Mean Change in Prevalence (%)**	**Standard Deviation**
Taxus	-22.22, -20.16	-21.19	1.03
Laurus	-19.33	-19.33	N/A
Castanea	-12.72, -11.88	-12.30	0.42
Juniperus	-25.7, -24.21, -24.09, -23.63 ,-22.32, -21.34, -21.33, -20, -19.23, -18.16, -14.68, -14.09, -13.89, -12.13, -11.15, -8.11, -6.97, -5.26, -3.5, -1.35, -0.26, 1.67, 2.44	-9.23	7.8897
Erica	-18.58, -8.32, -6.36, -4.95, -3.85, -0.61	-7.11	5.6440
Prunus	-20, -18.98, -18.87, -18.75, -18.4, -16.25, -16, -15.91, -14.22, -12.77, -12.55, -12.4, -9.36, -9.04, -7.09, -6.78, -6.74, -6.51, -3.36, -2.25, 0, 0, 0, 1.32, 2.85, 3.27, 3.33, 5.41, 6.25, 26.68	-6.57	10.2347
Larix	-4.20	-4.20	N/A
Amygdalus	-11.29, -9.86, -9.31, -9, -7.31, -6.23, -5.92, -5.35, -5, -3.59, -2.41, -2.17, 2.47, 2.71, 4.31, 4.73	-3.95	5.0080
Pinus	-24, -22.11, -18.74, -12.41, -12.16, -10.98, -10.96, -9.9, -6.54, -6.27, -5.57, -5.4, -5.22, -4.79, -4.72, -3.65, -3.58, -3.23, -2.95, -2.79, -2.7, -2.4, -2.07, -1.83, -1.22, -1.12, -0.97, -0.87, -0.84, -0.75, -0.75, -0.67, -0.66, -0.43, -0.39, -0.18, -0.18, -0.07, -0.07, -0.06, -0.02, 0, 0.22, 0.61, 2.27, 4.75, 5.13, 5.92, 9.94	-3.38	6.3612
Picea/Larix	-6.63, -4.43, -2.13, -1.78, -0.99, 2.78	-2.20	2.9167
Hippophae	2.17	2.17	N/A
Populus	-1.09, 7.41	3.16	4.25
Buxus	-0.08, 0.28, 1.05, 1.23, 3.4, 3.85, 4.05, 4.55, 4.76, 6.52, 6.67, 9.09	3.78	2.6916
Ulmus	-10.22, -2.67, -0.2, 2.44, 3.2, 3.16, 7.4, 10.25, 13.16, 13.33, 14.57	4.95	7.3333
Picea	0.1, 10.82	5.46	5.36
Sambucus	2.58, 6.71, 8.11	5.80	2.3475
Ulex	6.10	6.10	N/A
Sorbus	4, 7.86, 8.11, 9.9, 14.49	8.87	3.4047
Hedera	9.09	9.09	N/A
Acer	-5, -3.14, -2.84, -1.04, 0.21, 1.12, 1.5, 3.01, 4.37, 4.53, 9.4, 9.69, 11.96, 16.22, 17.03, 19.74, 20.08, 20.24, 20.7, 22.48, 22.65	9.19	9.3908
Carpinus	1.89, 4.54, 4.63, 9.3, 16, 16.41, 20.5	10.47	6.6625
Cytisus	11.59	11.59	N/A

Genus	**Changes in Prevalence following 350°C recalibration (%)**	**Mean Change in Prevalence (%)**	**Standard Deviation**
Fraxinus	-3, -2.76, -0.97, 2.33, 4.8, 5.56, 7, 10.65, 13.33, 13.88, 18.18, 18.18, 18.92, 20.47, 20.79, 21.88, 22.5, 23.68, 24.03	12.60	9.1347
Pyrus	13.51	13.51	N/A
Olea	2.63, 4.31, 4.91, 5.31, 7.21, 8.51, 8.88, 11.11, 18.7, 18.9, 29.11, 32.61, 33.06	14.25	10.6531
Crataegus	14.81	14.81	N/A
Quercus	1.74, 3.38, 3.95, 4.35, 4.39, 4.69, 5.33, 5.46, 7.44, 7.89, 8.51, 8.92, 9.59, 10.05, 10.4, 10.6, 11.88, 12.37, 12.76, 12.87, 13.79, 15.86, 16.51, 17.07, 17.89, 18.17, 19.17, 19.18, 20.19, 21.16, 21.47, 21.62, 21.86, 21.93, 22.34, 22.52, 24, 24.24, 24.49, 25.5, 27.03, 27.14, 28.16, 30, 31.58, 32.61	16.13	8.4161
Salix	2.08, 6.67, 14.75, 16.3, 17.69, 22.19	17.10	11.2835
Juglans	16.22, 19.74	17.98	1.76
Salix-Populus	2.5, 15.38, 15.56, 16.11, 16.67, 17.35, 17.5, 17.91, 19.23, 19.61, 21.05, 21.83, 23.87, 26.67, 27.59	18.59	5.6778
Viburnum	20	20	N/A
Corylus	16.08, 18.52, 18.92, 20.71, 22.33, 23.68, 29.73	21.42	4.1174
Ficus	23.08, 23.08	23.08	N/A
Arbutus	29.76, 32.32, 34.91	32.33	2.1025
Betula	19.22, 20.84, 22.25, 26.91, 29.21, 32.13, 32.89, 34.42, 34.45, 34.59, 35.67, 37.84, 41.67, 43.9, 50	33.07	8.2690
Cornus	33.78	33.78	N/A
Fagus	43.24	43.24	N/A

Correlation between conversion rates and changes in prevalences are obviously apparent (see Graph 8.1 beneath). The imperfect correlation is due to varying different genera also present with each genus in a site, and also the different number of times each genera appears (genera appearing in more sites will create means closer to its expected value).



Graph 8.1: the strong negative correlation between expected wood-to-charcoal conversion rates and real-life changes in prevalence at Neanderthal sites (R2 = 0.774).

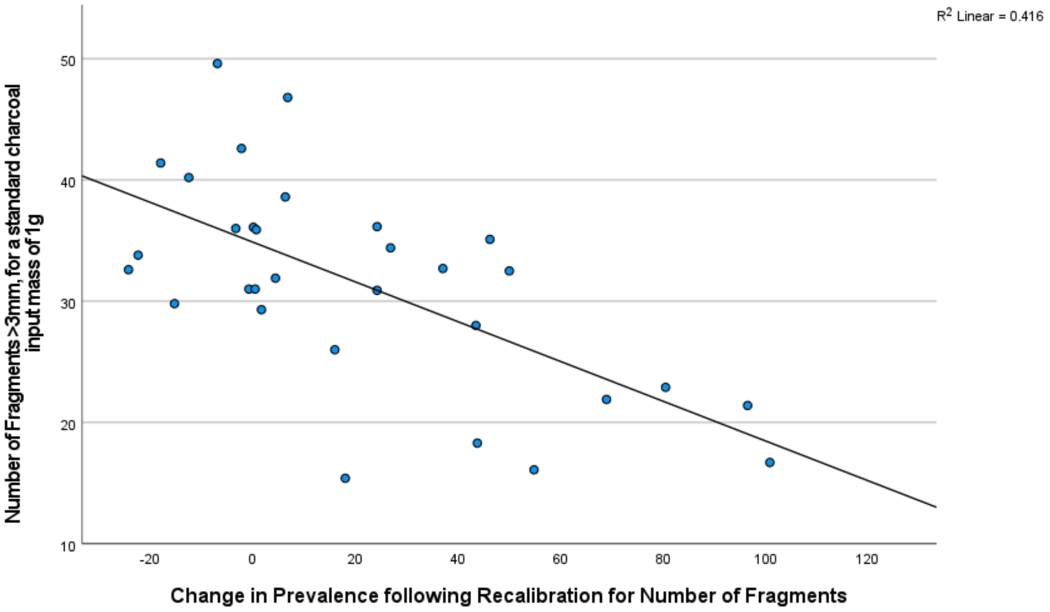
Similar changes in prevalences emerge when we also recalibrate for fragmentation bias, although to a much larger degree, as expected from the wider range of numbers of fragments, compared to smaller ranges of wood-to-charcoal conversion values. *Quercus*, producing extremely low numbers of >3mm fragments, affects many site results, and thus when recalibrated will drastically increase in prevalence, at the expense of other genera in the level. This is particularly noticeable in Klissoura. The standard deviations here are much larger than in the changes of prevalence following 350°C recalibrations, as expected from the much wider range of numbers of fragments.

Table 8.13: mean changes in prevalence of the various taxa where fragmentation-bias recalibrations are applied.

Genus	**Change in Prevalence following Fragmentation and 350°C Recalibrations (%)**	**Mean Change in Prevalence (%)**	**Standard Deviation**
Amygdalus	-44.71, -41.06, -36.63, -35.11, -32.95, -32.94, -27.64, -24.21, -22.63, -22.48, -16.26, -14.92, -13.11, -12.83, -10.07, -1.02	-24.29	12.3476
Juniperus	-55.29, -52.55, -48.74, -45.77, -45.45, -41.5, -38.96, -37.31, -36.84, -32.32, -29.41, -26.92, -17.79, 2.54, 4.29, 7.41, 8.5, 10.07, 13.33, 14.25	-22.42	24.998
Populus	-36.04, 0	-18.02	-----------
Prunus	-46.4, -45.95, -42.34, -38.36, -36, -26, -22.92, -18.63, -14.73, -12.13, -3.25, 25, 30.48, 36.73	-15.32	28.2357
Pinus	-54.53, -48, -45.79, -41.7, -41.46, -11.19, -11.16, -9.64, -9.27, -7.73, -6.61, -6.09, -4.71, -2.78, -2.01, -1.76, -1.04, -0.04,67.4	-12.53	26.8722

Genus	**Change in Prevalence following Fragmentation and 350°C Recalibrations (%)**	**Mean Change in Prevalence (%)**	**Standard Deviation**
Arbutus	-18.16, 4.27	-6.95	15.8604
Picea/Larix	-3.72, -3.01	-3.37	0.502
Sorbus	-3.3, -1.2	-2.25	1.4849
Acer	-37.7, -33.8, -28.71, -24.72, -24.68, -18.68, -15, -12.97, -6, -4.39, -2.37, -1.95, 1.05, 42.55, 44.94, 53.02, 55.8	-0.8	30.7816
Larix	0.06	0.06	N/A
Olea	-28.26, -22.87, -21.02, -18.44, -11.97, -7.82, -5.86, -5.69, 1.83, 4.44, 53.16, 67.39	0.41	29.7919
Picea	-4.68, 5.95	0.64	7.5165
Erica	-37.61, -2.16, 21.78, 24.55	1.64	28.7836
Fraxinus	-34.31, -15, -7.27, -3.33, 41.58, 44.55	4.37	31.8281
Corylus	-5.92, 18.52	6.3	17.2817
Cornus	6.76	6.76	N/A
Ulmus	-27.01, 4.88, 70	15.96	49.4445
Laurus	18	18	N/A
Salix/Populus	19.39, 21.62, 31.58	24.2	6.4906
Salix	-22.67, -8.3, 17.77, 54.21, 80	24.2	42.7453
Cytisus	26.83	26.83	N/A
Crataegus	37.04	37.04	N/A
Hippophae	43.48	43.48	N/A
Carpinus	43.76	43.76	N/A
Betula	38.12, 41.19, 43.44, 45.86, 62.5	46.22	9.5369
Viburnum	50	50	N/A
Rhamnus	-20, -1.61, 4.38, 18.26, 47.56, 50.34, 123.76, 125.93, 144.74	54.82	61.8778
Buxus	39.84, 77.03, 90	68.96	26.0363
Ulex	80.49	80.49	N/A
Quercus	16.29, 37.02, 38.74, 47.9, 50.13, 51.98, 59.02, 59.96, 62.82, 64.83, 65.85, 68.22, 84.46, 90.14, 94.06, 94.08, 103.64, 107.76, 112.16, 118.11, 122.99, 146.98, 215.15, 250, 250	96.49	61.9
Castanea	98.02, 103.64	100.83	3.9739

Correlation between fragmentation rates and changes in prevalences are strong (Graph 8.2, beneath), but not as perfectly correlated as Graph 8.1 for prevalences compared to expected 350°C conversion rates. This is due to *Quercus'* low fragmentation values dragging down other genera's prevalence values when sharing the same levels. Likewise, genera appearing only once tend to have higher average changes in prevalence.



Graph 8.2: the weaker negative correlation between expected number of fragments and real-life changes in prevalence at Neanderthal sites, once fragmentation-bias recalibration had occurred (R2 = 0.416).

I: The Iberian Sites.

The detailed data in the Iberian Peninsula sites allow a unique understanding of how pollen and charcoal records interact. The following Tables, 8.14-8.23, adapt the original charcoal-pollen discrepancies from Chapter Five.

I.I: Methodology.

For each layer of each site, I calculate the original amount of charcoal for each genus, following the recalibration tables on p.175.

For instance: Genus A has 10% of the charcoal, Genus B has 30% and Genus C has 60%. Under identical conditions, Genus A produces half the charcoal of Genus B, and Genus C produces twice as much (A = 0.5, B = 1 and C = 2 in ratios).

A: 10 ÷ 0.5 = 20

B: 30 ÷ 1 = 30

C: 60 ÷ 2 = 30

However, these proportions do not represent the final proportions, as 20 + 30 + 30 = 80

As all percentages should be out of 100, therefore:

A: (20 ÷ 80) x 100 = 25%

B: (30 ÷ 80) x 100 = 37.5%

C: (30 ÷ 80) x 100 = 37.5%

These represent the original *fuelwood* proportions instead of the current *charcoal* proportions. As in Chapter Five (p.144) I calculated the charcoal-pollen discrepancy for each genus through the equation:

Discrepancy = %(Charcoal)A - %(Pollen)A

So here I used:

Discrepancy = %(Fuelwood)A - %(Pollen)A

This produced similar results, but took charcoal production bias into account. The implications are identical to those on p.144; positive values means selection towards that genus compared to environmental availability, negative values means selection against it, and values of 0 means no selection (potentially representing the Principle of Least Effort).

In certain sites, charcoal was exclusively gathered through hand-picking (Abric Romani and Cova de Coll Verdaguer). This introduces further fragmentation biases, noted on p.170. In these two sites I also recalibrate for that bias. Using the fuelwood values (in the above example, A = 25%, B = 37.5%, C = 37.5%), I further recalibrate using recalibration tables on p.193. This works under identical principles to the calculations above, and again, discrepancies are calculated through %(Fuelwood)A - %(Pollen)A. Here however, the %(Fuelwood) value takes both charcoal production *and* fragmentation into account.

I.II: Results.

Table 8.14-8.23: Recalibrated charcoal-pollen discrepancies for the original 10 Middle Palaeolithic Iberian sites.

8.14: El Esquilleu Level IX-XIII			
Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**
Alnus	5.40 (P)	5.40 (P)	5.40 (P)
Betula	3.70 (P)	1.56 (P)	7.74 (P)
Corylus	12.76 (P)	12.76 (P)	12.76 (P)
Pinus	13.49 (P)	17.59 (P)	16.29 (C)
Sorbus	48.96 (C)	50.92 (C)	23.22 (C)
Ulmus	13.60 (P)	13.60 (P)	13.60 (P)
Total Discrepancy	**48.96**	**50.92**	**39.51**

8.15: El Esquilleu Level XIV-XIX			
Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**
Betula	18.90 (P)	18.37 (P)	19.91 (P)
Pinus	44.82 (C)	43.98 (C)	47.36 (C)
Sorbus	2.14 (C)	2.45 (C)	0.61 (C)
Ulmus	28.07 (P)	28.07 (P)	28.07 (P)
Total Discrepancy	**46.96**	**46.43**	**47.97**

8.16: El Esquilleu Level XX-XXX			
Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**
Alnus	4.66 (P)	4.66 (P)	4.66 (P)
Betula	13.73 (P)	12.91 (P)	15.29 (P)
Pinus	51.52 (C)	50.7 (C)	53.08 (C)
Quercus (deciduous)	8.00 (P)	8.00 (P)	8.00 (P)
Salix	8.11 (P)	8.11 (P)	8.11 (P)
Ulmus	17.02 (P)	17.02 (P)	17.02 (P)
Total Discrepancy	**51.52**	**50.70**	**53.08**

8.17: Cova de Coll Verdaguer Unit I

Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**	**Charcoal-Pollen Discrepancy for Fragmentation Bias (and 350°C conversion)**
Betula	1.38 (P)	1.38 (P)	1.38 (P)	1.38 (P)
Buxus	0.69 (P)	0.69 (P)	0.69 (P)	0.69 (P)
Juniperus	1.38 (P)	1.38 (P)	1.38 (P)	1.38 (P)
Olea	0.69 (P)	0.69 (P)	0.69 (P)	0.69 (P)
Pinus	6.68 (P)	7.26 (P)	2.15 (C)	12.44 (P)
Prunus	10.53 (C)	10.87 (C)	2.27 (C)	14.16 (C)
Quercus (deciduous)	0.30 (C)	0.54 (C)	0.27 (P)	2.43 (C)
Total Discrepancy	**10.83**	**11.41**	**4.42**	**16.59**

8.18: Cova de Coll Verdaguer Unit II

Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**	**Charcoal-Pollen Discrepancy for Fragmentation Bias (and 350°C conversion)**
Acer	0.39 (P)	0.39 (P)	0.39 (P)	0.39 (P)
Alnus	0.93 (P)	0.93 (P)	0.93 (P)	0.93 (P)
Betula	0.39 (P)	0.39 (P)	0.39 (P)	0.39 (P)
Buxus	0.47 (P)	0.47 (P)	0.47 (P)	0.47 (P)
Juniperus	3.47 (P)	3.47 (P)	3.47 (P)	4.37 (P)
Olea	0.78 (P)	0.78 (P)	0.78 (P)	0.78 (P)
Pinus	3.62 (C)	3.45 (C)	7.32 (C)	1.71 (C)
Prunus	4.43 (C)	4.60 (C)	0.73 (C)	6.34 (C)
Quercus (deciduous)	1.62 (P)	1.62 (P)	1.62 (P)	1.62 (P)
Total Discrepancy	**8.05**	**8.05**	**8.05**	**8.05**

8.19: Gorham's Cave Level IV			
Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**
Arbutus	3.04 (P)	3.04 (P)	3.04 (P)
Betula	1.53 (P)	1.53 (P)	1.53 (P)
Corylus	1.11 (P)	1.11 (P)	1.11 (P)
Erica	1.65 (C)	1.64 (C)	0.14 (C)
Fraxinus	2.53 (P)	2.53 (P)	2.53 (P)
Ilex	12.17 (P)	12.17 (P)	12.17 (P)
Juniperus	37.28 (P)	37.34 (P)	37.7 (P)
Olea	1.38 (P)	0.56 (P)	3.20 (P)
Pinus	68.98 (C)	68.27 (C)	72.77 (C)
Pistacia	7.92 (P)	7.92 (P)	7.92 (P)
Quercus (mixed)	1.05 (P)	1.05 (P)	1.05 (P)
Salix	2.67 (P)	2.67 (P)	2.67 (P)
Total Discrepancy	**70.63**	**69.91**	**72.91**

8.20: Cueva del Camino Level V			
Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**
Alnus	19.92 (P)	19.92 (P)	19.92 (P)
Betula	5.62 (C)	7.84 (C)	1.16 (C)
Corylus	14.49 (P)	14.49 (P)	14.49 (P)
Fraxinus	0.40 (C)	0.49 (C)	0.62 (C)
Olea	2.47 (P)	2.47 (P)	2.47 (P)
Pinus	40.57 (C)	38.09 (C)	45.29 (C)
Quercus (deciduous)	4.20 (P)	4.08 (P)	4.44 (P)
Salix-Populus	0.53 (P)	0.46 (P)	0.76 (P)
Ulmus	5.00 (P)	5.00 (P)	5.00 (P)
Total Discrepancy	**46.59**	**46.42**	**47.07**

8.21: Abric Romani Zone V

Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**	**Charcoal-Pollen Discrepancy for Fragmentation Bias (and 350°C conversion)**
Acer	1.81 (C)	2.22 (C)	0.74 (C)	2.82 (C)
Hippophae	0.46 (C)	0.47 (C)	0.79 (C)	0.66 (C)
Juniperus	7.25 (P)	7.25 (P)	7.25 (P)	7.25 (P)
Olea	0.46 (C)	0.61 (C)	0.12 (C)	0.77 (C)
Pinus	22.67 (C)	21.94 (C)	24.02 (C)	19.98 (C)
Prunus	0.00	0.00	0.00	0.00
Quercus (deciduous)	8.17 (P)	8.02 (P)	8.45 (P)	7.02 (P)
Rhamnus	9.96 (P)	9.96 (P)	9.96 (P)	9.96 (P)
Discrepancy	**25.40**	**25.24**	**25.67**	**24.23**

8.22: Abric Romani Zone IV

Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**	**Charcoal-Pollen Discrepancy for Fragmentation Bias (and 350°C conversion)**
Juniperus	6.85 (P)	6.85 (P)	6.85 (P)	6.85 (P)
Pinus	8.03 (C)	8.01 (C)	8.06 (C)	7.99 (C)
Quercus (deciduous)	1.22 (P)	1.22 (P)	1.22 (P)	1.22 (P)
Salix	0.05 (C)	0.07 (C)	0.02 (C)	0.09 (C)
Discrepancy	**8.08**	**8.08**	**8.08**	**8.08**

8.23: Abric Romani Zone III

Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**	**Charcoal-Pollen Discrepancy for Fragmentation Bias (and 350°C conversion)**
Juniperus	5.19 (P)	5.19 (P)	5.19 (P)	5.19 (P)
Olea	1.39 (P)	1.39 (P)	1.39 (P)	1.39 (P)
Pinus	29.49 (C)	29.49 (C)	29.58 (C)	29.44 (C)
Prunus	0.13 (C)	0.13 (C)	0.04 (C)	0.18 (C)
Quercus (deciduous)	5.57 (P)	5.57 (P)	5.57 (P)	5.57 (P)
Rhamnus	17.47 (P)	17.47 (P)	17.47 (P)	17.47 (P)
Discrepancy	**29.62**	**29.62**	**29.62**	**29.62**

If differences between charcoal and pollen were primarily attributable to differing wood-to-charcoal rates, once these were considered, the discrepancies (total positive or negative deviation from equal, random gatherings from distributions of local species accurately represented by the pollen) should tend towards zero, compared with uncalibrated samples. However, this is not the case. Three levels (Cova de Coll Verdaguer Unit II and Abric Romani Zones IV and III) show identical discrepancies in all sets, and maximum increases and decreases were 5.36% and 59.19% respectively. The mean increase in the discrepancy however, 2.84%, was much less than the mean decrease of 11.89%. This suggests that differential charcoal production may have partially caused discrepancy between pollen and charcoal distributions in some sites, but that its effects work both ways, increasing discrepancies in others.

Recalibrating for burning at 350°C causes minor increases in discrepancy of 0.66%; recalibration for 700°C causes larger decreases of 9.71%. This is despite most increased discrepancies (5/7) being from 700°C recalibrations, and 5/7 of decreased discrepancies being from 350°C recalibrations. This can partially be explained by the two 700°C decreases, 19.30% and 59.19%, being the largest decreases of discrepancies; the two increases at 350°C, 4.00% and 5.36%, are also the largest increases, although with smaller magnitudes. In both instances, at El Esquilleu Level IX-XIII and Cova de Coll Verdaguer Unit I, dominating *Pinus* was more abundant in environmental pollen than in anthropogenic charcoal, and these sites provided two of the few instances where 700°C recalibration changed *Pinus'* pollen dominance into a charcoal dominance, albeit at low levels in both instances. The latter level also causes *Quercus* to become pollen-dominant when recalibrated at 700°C. In both levels, *Pinus* is not overwhelmingly dominant in either pollen or charcoal records. Given minimal charcoal production at 700°C, and the tendency for its proportion to be increased when calibrated at this temperature, shifts from pollen-dominance to charcoal-dominance explain the extreme changes in discrepancies seen here. No change from charcoal-dominant to pollen-dominant selection, or vice-versa, was noted when recalibrating selections towards or against particular genera. There was only minor change at 350°C recalibration; at 700°C, five genera (*Acer, Erica, Hippophae, Prunus* and *Sorbus*) saw marked reductions in positive selection for fires:

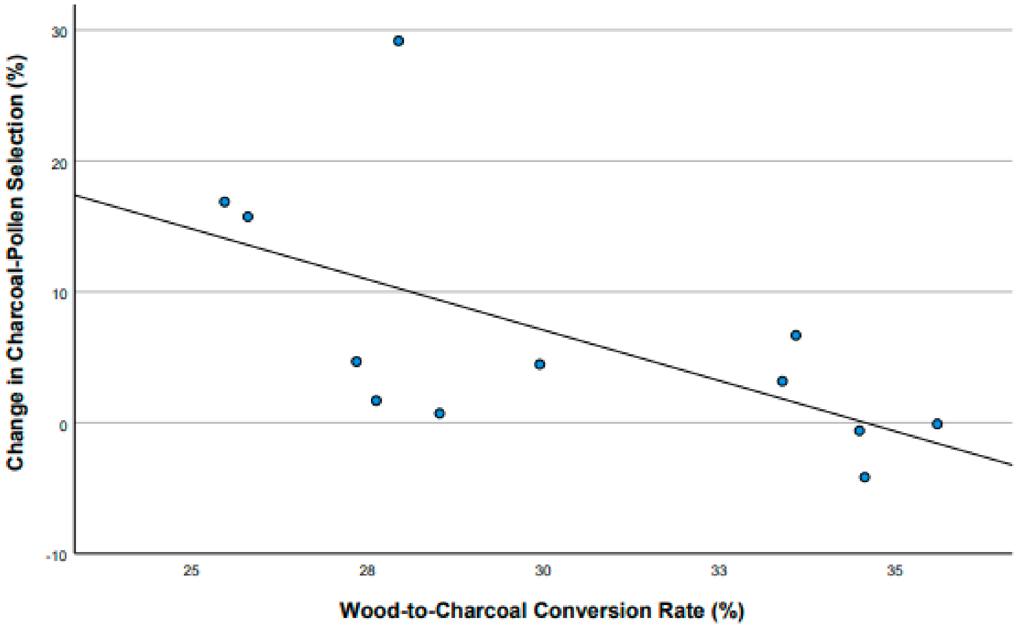
Table 8.24: the change in charcoal-pollen discrepancies for each genus following two sets of recalibration (350°C and 700°C). This only includes instances with charcoal for that genus present, where the charcoal-pollen discrepancy could possibly change with these recalibrations. The genera are ordered from lowest to highest (pre-recalibration) charcoal-pollen discrepancies.

Genus	**Charcoal-Pollen Discrepancy**	**Average**	**Charcoal-Pollen Discrepancy at 350˚C**	**Average**	**Charcoal-Pollen Discrepancy at 700˚C**	**Average**
Acer	1.81	1.81	2.22	2.22	0.74	0.74
Betula	-3.70, -18.90, -13.73, 5.62	-7.68	-1.56, -18.37, -12.91, 7.84	-6.25	-7.74, -19.91, -15.29, 1.16	-10.45
Erica	1.65	1.65	1.64	1.64	0.14	0.14
Fraxinus	0.40	0.40	0.49	0.49	0.62	0.62
Hippophae	0.46	0.46	0.47,	0.47	0.79	0.79
Juniperus	-37.28	-37.28	-37.34	-37.34	-37.70	-37.70
Olea	-1.38, 0.46	-0.46	-0.56, 0.61	0.03	-3.2, 0.12	-1.54
Pinus	-13.49, 44.82, 51.52, -6.68, 3.62, 40.57, 68.98, 22.67, 8.03, 29.49	24.95	-17.59, 43.98, 50.7, -7.26, 3.45, 38.09, 68.27, 21.94, 8.01, 29.49	23.91	16.29, 47.36, 53.08, 2.15, 7.32, 45.29, 72.77, 24.02, 8.06, 29.58	30.59
Prunus	10.53, 4.43, 0.13	5.03	10.87, 4.6, 0.13	5.20	2.27, 0.73, 0.04	1.01
Quercus	0.3, -4.2, -8.17	-4.02	0.54, -4.08, -8.02	-3.85	-0.27, -4.44, -8.45	-4.39
Salix	-0.53, 0.05	-0.24	-0.46, 0.07	-0.20	-0.76, 0.02	-0.37
Sorbus	48.96, 2.14	25.55	50.92, 2.45	26.69	23.22, 0.61	11.92

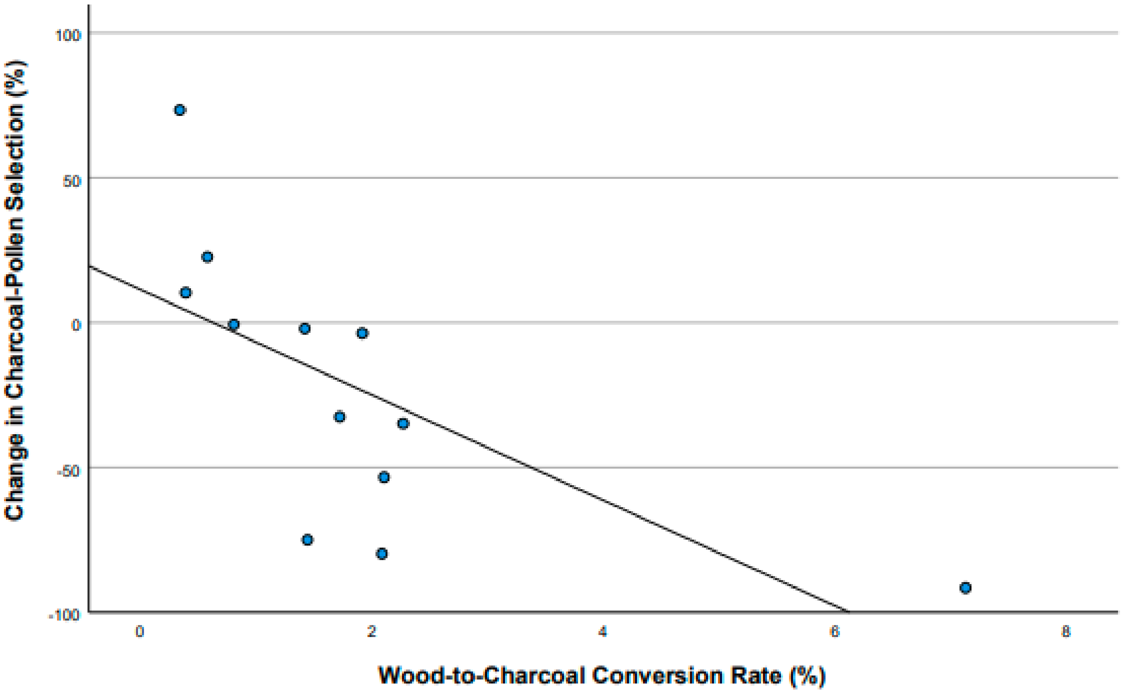
Correlations between wood-to-charcoal conversion rates and changed charcoal-pollen selections are present but not strong, as only those selection values with *any* charcoal presence changed through recalibration (see Graphs A28-A29, Appendix Seven). Those with no charcoal and only pollen (hence negative selection values) remain identical post-recalibration. As an example, more charcoal of Genus A means more of that genus was burnt. If Genus A produced abundant charcoal initially, amounts of wood originally burnt (and thus positive selection towards being burnt) would diminish on recalibration, whilst opposite effects happen to genera producing little charcoal. However, two scenarios exist, in sites A and B.

- In Site A, Genus A has abundant charcoal and minimal pollen presence. It therefore shows an initial strong positive selection as a fuel; following recalibrations, this selection is still positive but less strong.
- In Site B, Genus A has no charcoal and abundant pollen presence. It therefore shows an initial strong negative selection as a fuel, being environmentally-abundant but never

chosen. Following recalibrations, as there is no charcoal to recalibrate, this strong negative selection value remains identical.



Graph 8.3: A negative correlation at the 350˚C recalibration, where pollen-dominance is increasingly apparent in genera with higher wood-to-charcoal conversion rates. R² = 0.369.



Graph 8.4: Another negative correlation at the 700˚C recalibration, where once again, genera with lower wood-to-charcoal conversion rates become more charcoal-dominated when recalibrated. R² = 0.462.

Finally, when fragmentation bias is considered in the two potentially-relevant sites, it minimally altered overall records or selection processes. In each instance, it somewhat reduces preference towards *Pinus*, somewhat increasing preference towards *Prunus*. Only in Cova de Coll Verdaguer Unit I does this recalibration create any pronounced effect, whereby selection against *Pinus* seems to double, and selection towards *Prunus* notably increase. These effects probably result from only recalibrating two sites, with neither containing *Quercus* charcoal, a genus notably creating few charcoal fragments. Whilst fragmentation bias is an important factor, as shown in Table 7.17, neither set of recalibrations greatly change the picture where we can determine fuel selection.

Some additional Neanderthal site reports also contain complementary pollen diagrams alongside their charcoal records, including Bolomor Cave (Ochando et al. 2019), Cueva Anton (Zilhao et al. 2016), Riparo Bombrini (Arobba and Caramiello 2009) and Teixoneres Cave (Ochando et al. 2020). These are displayed beneath, alongside their changed charcoal-pollen difference values at the two recalibration values. Riparo Bombrini additionally has fragmentation bias recalibrations, from excavators only practicing hand-picking.

Table 8.25-8.29: effects of recalibrations on charcoal-pollen discrepancies in non-Iberian Middle Palaeolithic sites.

8.25: Cueva Anton Complex AS3			
Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350˚C**	**Charcoal-Pollen Discrepancy for 700˚C**
Juglans	0.22 (P)	0.22 (P)	0.22 (P)
Juniperus	12.82 (C)	12.26 (C)	9.91 (C)
Olea	0.45 (P)	0.45 (P)	0.45 (P)
Pinus	11.72 (P)	12.69 (P)	4.15 (P)
Quercus	0.43 (P)	1.10 (C)	5.09 (P)
Total Discrepancy	**12.82**	**13.36**	**9.91**

(84.8% of arboreal pollen used).

8.26: Cueva Anton Complex AS5			
Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**
Erica	0.26 (C)	0.25 (C)	0.03 (C)
Juniperus	15.17 (C)	14.20 (C)	12.99 (C)
Pinus	30.5 (P)	32.97 (P)	17.58 (P)
Prunus	0.39 (C)	0.39 (C)	0.13 (C)
Quercus	13.79 (C)	17.08 (C)	4.00 (C)
Salix-Populus	0.90 (C)	1.05 (C)	0.44 (C)
Total Discrepancy	**30.5**	**32.97**	**17.58**

(85% of arboreal pollen used).

8.27: Bolomor Cave Levels XI & XIII			
Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**
Alnus	0.14 (P)	0.14 (P)	0.14 (P)
Arbutus	0.7 (P)	0.7 (P)	0.7 (P)
Arctostaphylos	0.14 (P)	0.14 (P)	0.14 (P)
Betula	0.35 (P)	0.35 (P)	0.35 (P)
Castanea	4.73 (P)	4.73 (P)	4.73 (P)
Corylus	0.35 (P)	0.35 (P)	0.35 (P)
Erica	5.54 (P)	5.54 (P)	5.54 (P)
Fraxinus	3.94 (P)	3.94 (P)	3.94 (P)
Juniperus	4.80 (C)	4.60 (C)	2.83 (C)
Myrica	0.23 (P)	0.23 (P)	0.23 (P)
Myrtus	1.96 (P)	1.96 (P)	1.96 (P)
Olea	10.11 (P)	10.11 (P)	10.11 (P)
Phillyrea	1.39 (P)	1.39 (P)	1.39 (P)
Pinus	60.80 (C)	61.00 (C)	62.77 (C)
Pistacia	1.12 (P)	1.12 (P)	1.12 (P)
Populus	2.60 (P)	2.60 (P)	2.60 (P)
Quercus	28.87 (P)	28.87 (P)	28.87 (P)
Rhamnus	0.79 (P)	0.79 (P)	0.79 (P)
Salix	1.86 (P)	1.86 (P)	1.86 (P)
Sambucus	0.13 (P)	0.13 (P)	0.13 (P)
Viburnum	0.54 (P)	0.54 (P)	0.54 (P)
Total Discrepancy	**65.6**	**65.6**	**65.6**

(94.83% of arboreal pollen used).

8.28: Riparo Bombrini Stratum IV				
Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**	**Charcoal-Pollen Discrepancy for Fragmentation Bias (and 350°C conversion)**
Abies	0.88 (P)	0.88 (P)	0.88 (P)	0.88 (P)
Alnus	1.46 (P)	1.46 (P)	1.46 (P)	1.46 (P)
Arbutus	12.50 (C)	16.22 (C)	2.90 (C)	10.23 (C)
Buxus	25.00 (C)	24.48 (C)	13.66 (C)	34.96 (C)
Carpinus	0.29 (P)	0.29 (P)	0.29 (P)	0.29 (P)
Castanea	0.88 (P)	0.88 (P)	0.88 (P)	0.88 (P)
Corylus	11.62 (C)	13.63 (C)	13.19 (C)	10.88 (C)
Erica	12.50 (C)	11.46 (C)	2.53 (C)	12.23 (C)
Fagus	0.29 (P)	0.29 (P)	0.29 (P)	0.29 (P)
Fraxinus	4.68 (P)	4.68 (P)	4.68 (P)	4.68 (P)
Juniperus	37.50 (C)	33.32 (C)	66.84 (C)	30.83 (C)
Olea	0.58 (P)	0.58 (P)	0.58 (P)	0.58 (P)
Ostrya	1.75 (P)	1.75 (P)	1.75 (P)	1.75 (P)
Phillyrea	1.46 (P)	1.46 (P)	1.46 (P)	1.46 (P)
Pinus	80.41 (P)	80.41 (P)	80.41 (P)	80.41 (P)
Quercus	4.39 (P)	4.39 (P)	4.39 (P)	4.39 (P)
Rhamnus	0.29 (P)	0.29 (P)	0.29 (P)	0.29 (P)
Sambucus	1.17 (P)	1.17 (P)	1.17 (P)	1.17 (P)
Ulmus	0.29 (P)	0.29 (P)	0.29 (P)	0.29 (P)
Vitis	0.29 (P)	0.29 (P)	0.29 (P)	0.29 (P)
Total Discrepancy	**99.12**	**99.11**	**99.12**	**99.13**

(100% of arboreal pollen used).

8.29: Teixoneres Cave Levels II, IIb and III			
Genus	**Original Charcoal-Pollen Discrepancy**	**Charcoal-Pollen Discrepancy for 350°C**	**Charcoal-Pollen Discrepancy for 700°C**
Betula	0.91 (P)	0.91 (P)	0.91 (P)
Buxus	26.42 (C)	26.50 (C)	6.99 (C)
Castanea	5.20 (P)	5.20 (P)	5.20 (P)
Corylus	2.59 (P)	2.59 (P)	2.59 (P)
Erica	3.56 (P)	3.56 (P)	3.56 (P)
Fraxinus	1.31 (P)	1.31 (P)	1.31 (P)
Juglans	0.48 (P)	0.48 (P)	0.48 (P)
Juniperus	11.96 (P)	11.96 (P)	11.96 (P)
Myrtus	0.63 (P)	0.63 (P)	0.63 (P)
Olea	0.60 (P)	0.60 (P)	0.60 (P)
Pinus	33.45 (C)	29.87 (C)	59.23 (C)
Pistacia	0.48 (P)	0.48 (P)	0.48 (P)
Populus	1.43 (P)	1.43 (P)	1.43 (P)
Quercus	28.89 (P)	25.39 (P)	35.24 (P)
Rhamnus	0.36 (P)	0.36 (P)	0.36 (P)
Salix	0.95 (P)	0.95 (P)	0.95 (P)
Sambucus	0.17 (P)	0.17 (P)	0.17 (P)
Taxus	0.36 (P)	0.36 (P)	0.36 (P)
Total Discrepancy	**59.87**	**56.37**	**66.22**

(86.24% of arboreal pollen used).

As with the Iberian study, many more genera are found as pollen than charcoal in these sites; as expected if Neanderthals selected limited local fuelwoods. Bolomor Cave Neanderthals only burnt 2 genera out of a potential 21; 3 in Cueva Anton AS3 out of 5, and 3 in Teixoneres Cave out of 18. Cueva Anton AS5 however presents a peculiar picture, where only two genera are present as pollen (*Pinus* and *Quercus*), but six as charcoal. Likewise in Pod Hradem Cave (excluded from these analyses because of <5% of the pollen being identified to the genus level), there were more genera present as charcoal than as pollen (5 charcoal genera v 1 pollen genus in Level 9, 4 charcoal v 3 pollen in Level 10, and 3 charcoal v 2 pollen in Level 11). However, here this may result from low levels of pollen identification. Riparo Bombrini Stratum IV presents an even stranger picture; only one genus (*Corylus*) exists in both records, four are found exclusively as charcoal, and fifteen exclusively found as pollen. Occasional winds may have collected pollen from completely separate areas to where Neanderthals foraged; especially if Riparo Bombrini was on the boundary between two ecosystem types.

Alternatively, these Neanderthals may have foraged deadwood from other biomes as deadwood from stream systems.

Fragmentation-bias recalibration for Riparo Bombrini shows larger effects here than in other sites. Several genera are minorly reduced in positive selection for fuelwood compared to environmental availability, including an almost 7% decrease in the use of *Juniperus*, and consequently, an almost 10% increase in the use of *Buxus*. Box is not commonly perceived as a "good" fuelwood, and neither are most of the other burned woods, apart from perhaps juniper. This further suggests that this site represents different burning choices to much of the rest of the Neanderthal record, and possibly different foraging regimes. Many genera are found at very low quantities as pollen or charcoal, and would not have been a substantial part of either fires or environments in these five levels. If we remove all with charcoal-pollen discrepancies <5%, we find the following:

Table 8.30: charcoal-dominant and pollen-dominant genera at various recalibrated sites. These are not the same as those in Chapter Five; Pinus is frequently dominant in the pollen for instance.

Site and Level	**Charcoal-Dominant Genera**	**Pollen-Dominant Genera**
Bolomor Cave Levels XI & XIII	*Pinus*	*Erica, Olea, Quercus*
Cueva Anton Complex AS3	*Juniperus*	*Pinus*
Cueva Anton Complex AS5	*Juniperus, Quercus*	*Pinus*
Riparo Bombrini Stratum IV	*Arbutus, Buxus, Corylus, Erica, Juniperus*	*Pinus*
Teixoneres Cave Levels II, IIb and III	*Buxus, Pinus*	*Castanea, Juniperus, Quercus*

Unlike the previous Iberian sites, these do not show such pine-dominated charcoal records, and in fact 3/5 of them have higher proportions of *Pinus* in the pollen. *Juniperus* and *Quercus* are likewise not exclusively charcoal- or pollen-dominant, but their prevalence varies from site to site. The recalibrations to the various temperatures do not greatly change these pictures either – this is expected as these recalibrations will only alter genera present at all as charcoal.

II: All Neanderthal Sites.

When we expand the sites to include all Middle Palaeolithic ones with [anthropogenically-driven] charcoal records, the full recalibration effects become apparent, especially in the many non-pine-dominant examples. When the results are recalibrated for 350°C, the most likely charcoal-production temperature, in only one site (La Vina Cave) does the most common fuel type change through this recalibration, in this instance from *Pinus* to *Betula*. In Theopetra Layer II7, the two most common fuels (*Quercus* and *Prunus*), previously having a 10% difference, become near-identically prevalent post-recalibration. In this most probable recalibration then, the previously-dominant fuels in all Neanderthal fires still stand.

At 700°C however, the changes are much more dramatic. *Pinus,* having a low 700°C wood-to-charcoal conversion rate, and thus becoming much more prevalent through recalibration, does not stop being a dominant fuel in any site, becom dominant at four additional sites. These changes are naturally most likely in sites with close-to-equal proportions of multiple genera rather than where one genus completely dominates the record. Theopetra changed dominant genera in 5 of its 9 studied levels, and Klissoura in 4 of its 15.

Table 8.31: The changes in dominant fuel in the charcoal record following 700˚C recalibration.

Site Level	**Previous dominant fuel**	**Dominant fuel following 700˚C recalibration**
De Nadale Cave Unit 7	*Picea/Larix*	*Pinus*
El Esquilleu Level IX-XIII	*Sorbus*	*Pinus*
Klissoura Cave Layer XXI	*Olea*	*Quercus* (deciduous)
Klissoura Cave Layer XXg-XXe	*Olea*	*Juniperus*
Klissoura Cave Layer XV	*Amygdalus*	*Acer*
Klissoura Cave Layer XIV	*Amygdalus*	*Acer*
Pod Hradem Cave Level 11	*Picea/Larix*	*Pinus*
Pod Hradem Cave Level 9	*Picea/Larix*	*Pinus*
Scladina Cave Unit 4A	*Quercus*	*Pinus*
Theopetra Cave Layer II5	*Carpinus*	*Fraxinus*
Theopetra Cave Layer II6	*Carpinus*	*Fraxinus*
Theopetra Cave Layer II7	*Prunus*	*Quercus* (deciduous)
Theopetra Cave Layer II8	*Quercus* (deciduous)	*Fraxinus*
Theopetra Cave Layer II11	*Prunus*	*Juniperus*

II.I: Fragmentation-Bias Effects.

Alongside wood-to-charcoal recalibration analyses, what has been the overall effects of fragmentation bias analyses? Admittedly only 6 out of 15 levels with comparable pollen and charcoal (and 28 of 57 levels with only charcoal) have been thus analysed. Thus further analysis of the whole might produce different patterns; however this would not necessarily have been appropriate, as the other 38 levels were properly sieved and smaller (<3mm) charcoal fragments analysed, minimizing the effect of this potential bias. When pollen and charcoal are compared, fragmentation has minimally changed overall charcoal-pollen discrepancies in each direction; the exception is Cova de Coll Verdaguer Unit 1, where discrepancies increased from 10.83 to 16.59. Thus it appears unlikely that differential fragmentation by genus, alone or in combination with differential wood-to-charcoal conversion rates, created the differences between charcoal and pollen records. However, it could easily be responsible for individual preferences towards certain fuelwoods. Whilst *Pinus'* prevalence slightly reduces, it was clearly still strongly selected for compared to environmental availability, and is common on many sites. Juniper, on the other hand, whilst equally widespread among sites, appears to be slightly less popular than it first appeared, as does both *Prunus* and the related *Amygdalus*. On the flipside, *Rhamnus* and *Quercus* were both used commonly but sparingly; following these recalibrations, it appears that they may have been more popular fuelwoods than once thought. Given that most sites lack complementary pollen diagrams however, the impact of this on selectivity is unclear. When I compare recalibration effects on what is the most common fuel, *Quercus* almost universally becomes most common:

Table 8.32: The changes in dominant fuel in the charcoal record following fragmentation-bias recalibration.

Site Level	**Previous dominant fuel**	**Dominant fuel following Fragmentation-Bias recalibration**
Klissoura Layer XXI	*Olea*	*Quercus*
Klissoura Layer XXg-XXe	*Olea*	*Quercus*
Klissoura Layer XVI	*Amygdalus*	*Quercus*
Klissoura Layer XII	*Juniperus*	*Quercus*
Klissoura Layer VIII-VII	*Juniperus*	*Quercus*
Riparo Bombrini Stratum IV	*Juniperus*	*Buxus*

II.II: Trends of Preferred Fuels (Dominant Genera).

Although pine being the dominant genus is a defining Iberian trend, this is by no means universal, as seen in Table 8.33 below, which lists all those levels where *Pinus* is not the dominant genus.

Table 8.33: the first- and second-most dominant genera in all the studied Middle Palaeolithic sites, excluding Pinus-dominant layers.

Site and Level(s)/Unit(s)	Dominant Genus	Percentage of Assemblage	Second-Dominant Genus	Percentage of Assemblage
Abric del Pastor Unit IVc	*Juniperus*	56.47	*Pistacia*	26.79
Abric del Pastor Unit IVd	*Juniperus*	69.92	*Pistacia*	18.51
De Nadale Cave Unit 7	*Picea/Larix*	58.82	*Pinus*	30.15
El Esquilleu Levels IX-XIII	*Sorbus*	48.96	*Pinus*	41.42
Grotta di Fumane Unit A9	*Larix*	52.11	*Picea/Larix*	38.83
Kaldar Cave Layers 4-5	*Prunus*	52.94	*Amygdalus*	35.29
Klissoura Cave Layer XXI	*Olea*	41.27	*Quercus* deciduous	33.33
Klissoura Cave Layer XXg-XXe	*Olea*	28.57	*Quercus* deciduous/mixed	21.43
Klissoura Cave Layer XXd-c	*Quercus* deciduous/mixed	35.09	*Olea*	24.56
Klissoura Cave Layer XXb-a	*Quercus*	39.73	*Olea*	24.66
Klissoura Cave Layer XIX	*Olea*	73.13	*Quercus* deciduous	10.95
Klissoura Cave Layer XVIII	*Olea*	61.90	*Amygdalus*	23.33
Klissoura Cave Layer XVII	*Quercus*	33.08	*Amygdalus*	28.57
Klissoura Cave Layer XVI	*Amygdalus*	49.18	*Quercus*	30.05
Klissoura Cave Layer XV	*Amygdalus*	54.30	*Acer*	37.56
Klissoura Cave Layer XIV	*Amygdalus*	53.54	*Acer*	33.33
Klissoura Cave Layer XIII	*Acer*	66.67	*Amygdalus*	23.19

Site and Level(s)/Unit(s)	**Dominant Genus**	**Percentage of Assemblage**	**Second-Dominant Genus**	**Percentage of Assemblage**
Klissoura Cave Layer XII	*Juniperus*	40.16	*Acer*	28.69
Klissoura Cave Layer XI	*Juniperus*	49.64	*Acer*	24.09
Klissoura Cave Layers X-IX	*Quercus* deciduous	47.83	*Prunus*	17.39
Klissoura Cave Layers VIII-VII	*Juniperus*	40.74	*Amygdalus/Quercus*	25.93
Nesher Ramla Levels I-VIi1	*Quercus*	74.14	*Prunus*	24.14
Pod Hradem Cave Level 11	*Picea/Larix*	76.02	*Pinus*	23.39
Pod Hradem Cave Level 10	*Picea/Larix*	92.21	*Pinus*	5.74
Pod Hradem Cave Level 9	*Picea/Larix*	77.84	*Pinus*	19.16
Riparo Bombrini Stratum IV	*Juniperus*	37.5	*Buxus*	25
Scladina Cave Unit 4A	*Quercus* mixed	47.44	*Pinus*	30.77
Theopetra Cave Layer II3	*Prunus*	70	*Carpinus*	22
Theopetra Cave Layer II4A	*Prunus*	61.8	*Quercus* deciduous	16.85
Theopetra Cave Layer II4b	*Prunus*	80	*Sambucus*	7
Theopetra Cave Layer II5	*Carpinus*	37	*Quercus* deciduous	25
Theopetra Cave Layer II6	*Carpinus*	42.39	*Quercus* deciduous	32.61
Theopetra Cave Layer II7	*Prunus*	45	*Quercus* deciduous	35
Theopetra Cave Layer II8	*Quercus* deciduous	42.11	*Prunus*	36.84
Theopetra Cave Layer II10	*Juniperus*	96	*Prunus*	4
Theopetra Cave Layer II11	*Prunus*	41	*Juniperus*	35

In total, exactly half the layers studied (36 of 72) were pine-dominant, and half were dominated by other genera. If we consider the genera which were predominant and second-most-common in non-pine-dominant fires, their prevalences are as follows:

Table 8.34: comparing how widespread a dominant genus is (the number of sites it is dominant at) with its dominance within the record (what proportion of the fuel assemblage it represents in these dominant sites).

Genus	**Number of instances of being prevalent or second-most-common**	**Prevalence (calculated only from the instances where they are present as dominant or second-most-common)**
Sambucus	1	7%
Pistacia	2	22.65%
Buxus	1	25%
Carpinus	3	33.80%
Quercus	16	34.41%
Amygdalus	8	36.67%
Acer	5	38.07%
Olea	6	42.35%
Prunus	10	43.31%
Sorbus	1	48.96%
Juniperus	8	53.18%
Picea/Larix	5	79.17%

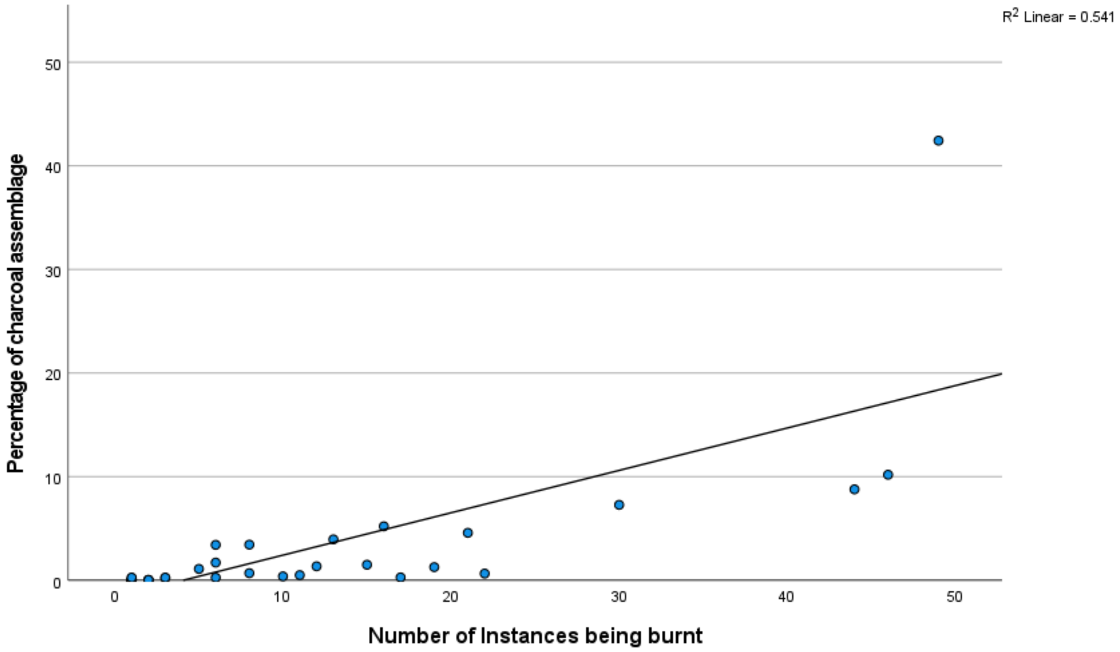
These prevalences indicate which genera Neanderthals would have recognized and used most in [non-pine-dominant] fires. The three most common dominating fuels, in terms of predominance in a single fire, are all conifers, as of course is the dominating *Pinus.* If we calculate *Pinus'* predominance in a similar manner, from the 42 layers where it is a most-common or second-most-common fuel, the average prevalence comes out at 73.47%. So although *Pinus* is by far the most common fuel in terms of *number of total layers it was dominant in*, it falls within the range for conifers in terms of *absolute abundance within a single layer. Picea/Larix* actually were more prevalent within single layers (in which they dominated), suggesting that *Pinus* was more likely to be burnt alongside other woods than them. We do not, of course, know most layers' fire compositions, and whether average fires were say c.79% *Picea/Larix* and 21% other genera, or whether 79% of fires exclusively burnt *Picea/Larix*, and 21% exclusively burnt other genera.

If Neanderthals selected their fuels, tendencies towards single-genus-dominant conifer fires and multiple-genus broadleaf-wood fires could indicate that conifer wood was optimal for all fires, and that broadleaf-wood required more specific selection for different fire stages/ functions. Alternatively, if Neanderthals selected only according to environmental availability, then it suggests that conifer biomes were more monospecific than diverse broadleaved forests, an observation confirmed by fuel-gathering studies (see Chapter Ten).

Table 8.35: an "average" Neanderthal fire, combining all fuel genera from all sites studied in direct proportion to their prevalence in the overall charcoal record across all sites. As yet this is the first instance of such a reconstruction; the much larger number of Upper Palaeolithic modern human sites, spread over a much wider geographical area with many more different kinds of trees, has thus far precluded a similar dataset for modern humans. Such an undertaking may be possible for a limited geographical region and/or time period, however that is outside the scope of this thesis.

Genus	**Number of Instances**	**Proportion within fires containing that genus**	**Proportion within all Neanderthal fires**
Viburnum	1	0.10	----
Crataegus	1	0.27	----
Celtis	1	0.30	----
Hedera	1	0.33	----
Ficus	2	0.26	0.01
Fagus	1	0.37	0.01
Pyrus	1	0.37	0.01
Hippophae	1	0.46	0.01
Cornus	1	0.74	0.01
Ulex	1	0.82	0.01
Juglans	2	0.57	0.02
Taxus	2	0.87	0.02
Laurus	1	1.50	0.02
Cytisus	1	1.64	0.02
Castanea	2	1.29	0.04
Phillyrea	1	15.25	0.21
Arbutus	3	5.28	0.22
Corylus	1	2.63	0.26
Erica	6	3.13	0.26
Sambucus	3	6.2	0.26
Populus	17	1.19	0.28
Rhamnus	10	2.75	0.38
Ulmus	11	3.26	0.50
Salix	22	2.14	0.65
Pistacia	8	6.23	0.69
Sorbus	5	15.83	1.10
Fraxinus	19	4.82	1.27
Buxus	12	8.11	1.35
Betula	15	7.18	1.50
Carpinus	6	20.46	1.71
Larix	6	41.01	3.42
Picea	8	30.96	3.44
Olea	13	21.88	3.95
Acer	21	15.71	4.58
Amygdalus	16	23.42	5.21
Prunus	30	17.48	7.28
Juniperus	44	14.36	8.78
Quercus	46	15.94	10.19
Pinus	49	62.36	42.44

Once again, pine dominates both sets of calculations in Table 8.35. It is particularly noticeable when analysed across all Neanderthal fires, that it is over four times as common as the next most common genus (*Quercus*). As with the analysis of first- and second-most dominant fuels, conifers once again are dominant, but only *within fires containing them at all*. However *Juniperus*, forming 53.18% of fuel in *Juniperus*-dominant fires, only forms 14.36% of fuel in *Juniperus*-using fires. A reduction in prevalence is expected, as counting all instances of a genus naturally includes those much smaller proportions to factor into the average. However, this reduction is much larger than in *Pinus* (73.47% to 62.36%), or *Picea/Larix* (79.17% to 30.96% or 41.01% respectively). *Picea* and *Larix* notably have very few instances, 8 and 6 respectively, and yet are dominant when found (in contrast to *Rhamnus*, which is frequently present at low levels). *Juniperus* on the other hand is extremely common, found in over half the fires, sometimes dominant and sometimes as a subsidiary addition. The exceptions are those fuels burnt commonly at consistently low levels, such as *Populus, Salix, Fraxinus* and *Betula*. This suggests that these fuels formed important starter or expedient subsidiary fuels, but were never considered main fuels, due to unwanted burning qualities or other reasons.



Graph 8.5: the positive correlation between the overall dominance of a genus across the whole Neanderthal charcoal record, and how many sites it is burnt at (R2 = 0.541).

II.III: Temporal Trends of Fuel Use.

When viewed graphically across all [dated] sites, no genus' use changes notably across time. I excluded some sites/layers due to a lack of reliable dating: Cova 120 Levels V-VI, Klissoura Cave Layer XXI, La Vina Cave Levels XIIIbas, XIV, XV, I.A, I.B, Les Canalettes Levels 3-4, Pod Hradem Cave Level 9, and Theopetra Cave Layers II3, and II5-II7. From the remainder, this lack of trends is expected, given wide varieties of site latitudes and local microclimates existing outside wider global trends. Additionally, given this study's wide scale, rapid MIS 5-3 glaciation cycles would be missed. Despite certain individual sites showing trends for one or more dominant genera (e.g. in Les Canalettes *Pinus* use increases whilst *Buxus* use declines), these are hidden in the wider picture. Certain genera are Mediterranean-adapted (e.g. *Pistacia*), others cold-loving (*Larix*), and many can be from multiple climates, with different cold- and warm-climate species within the genus (e.g. cold-adapted *Pinus sylvestris* versus warm-adapted *Pinus halepensis*). However, even those found across wide geographical ranges lack trends across time. This does not suggest 'evolving' fire strategies independent of environmental constraints, tending towards single or multiple 'optimal' fuelwoods. Instead, it suggests fuel choice mediated by local availability, and Neanderthals choosing from local fuelsets rather than collecting better fuels further afield. Similarly, intra-dataset varieties, representing numbers of different genera burnt in Neanderthal fires in that level (although not necessarily identical fires) remains steady through time (see Table 8.36 below, and Graph A45, p.408). This indicates a lack of increasing selectivity for single-fuel fires, or increasing diversification of gathering habits through time.

Table 8.36: the lack of correlation between the age of a site and the diversity of fuels found in the charcoal record. This is also presented in Graph A45, p.408.

Site	**Mean Age (ka BP)**	**Number of Genera found within the level**
Bolomor Cave Levels XI & XIII	195	2
Theopetra Cave Level II4a	128.5	6
Theopetra Cave Level II4b	128.5	5
Nesher Ramla Levels I-VIi1	125	3
Klissoura Cave Layer XXg-XXe	123.3	6
Klissoura Cave Layers XXd-c	116.7	5
Bojnice III Layer IX	105.1	4
Abrigo de la Quebrada Level VIII	105	6

Site	**Mean Age (ka BP)**	**Number of Genera found within the level**
Klissoura Cave Layer XXb-a	102.5	9
Scladina Cave Unit 4A	100	5
Klissoura Cave Layer XIX	93.9	8
Klissoura Cave Layer XVIII	92.8	7
Klissoura Cave Layer XVII	91.2	9
Cueva del Camino Level V	91	5
Klissoura Cave Layer XVI	82.5	5
Scladina Cave Unit 2B	82	4
Klissoura Cave Layer XV	78.8	5
Abric del Pastor Unit IVc	75	7
Abric del Pastor Unit IVd	75	7
Klissoura Cave Layer XIV	75	5
Les Canalettes Level 2	73.5	13
Cueva Anton Complex AS5	73.1	6
Cueva Anton Complex AS2	70.7	3
De Nadale Cave Unit 7	70.2	4
Cueva Anton Complex AS3	65	3
Klissoura Cave Layer XIII	64.5	4
Cova 120 Level IV	57.9	7
Klissoura Cave Layer XII	53.9	9
El Salt Unit Xa	52.3	8
El Salt Unit Xb AFA 1	52.3	7
El Salt Unit Xb AFA 2	52.3	9
El Salt Unit Xb AFA 3	52.3	5
Abric Romani Zone III	52.3	2
El Esquilleu Levels XX-XXX	52.3	2
El Salt Unit IX	52.2	7
El Salt Unit VIII	50.8	6
El Esquilleu Levels XIV-XIX	49.7	3
Abric Romani Zone IV	47.9	2
Klissoura Cave Layer XI	46.6	5
Klissoura Cave Layer X-IX	46.4	6
Aguilon P5	46	2
Kaldar Cave Layers 4-5	45.6	3
Klissoura Cave Layers VIII-VII	45.5	5
Pod Hradem Cave Level 11	45.2	3
Pod Hradem Cave Level 10	44.7	4
Abric Romani Zone V	44.4	5
Teixoneres Cave Levels II, IIb and III	43.8	3

Site	Mean Age (ka BP)	Number of Genera found within the level
Llonin Cave Levels VIII CP, IV Gal	43.5	3
Riparo Bombrini Stratum IV	43	5
Abri du Maras Layer 4	43	3
Cova del Coll Verdaguer Unit I	42.9	3
Cova del Coll Verdaguer Unit II	42.3	2
Grotta di Fumane Unit A9	41.2	5
Cova Gran S1B-S1F	40.5	5
Cueva del Conde Level N10	38	8
El Esquilleu Levels IX-XIII	37.8	3
Cueva del Conde Level N20A	37.5	15
Gorham's Cave Level IV	33	4

III: Conclusion.

This chapter has applied recalibrations to data obtained from archaeological sites, and discussed effects they have had on inferences about Neanderthal fuel foraging strategy. The effects of the 700°C recalibrations, although causing much more extreme changes in magnitude, are not applicable to all fuels as proportions of charcoal created at 700°C, compared to 350°C, are minimal. Fuels exclusively added as firestarters (*Erica* and *Hedera*) each decline in proportion by over 85% once recalibrated, further highlighting their minimal use. This suggests that Neanderthals either used leaves/grasses as firestarters, leaving no charcoal, or used the same easily-ignitable woods which they burnt later in fires, such as *Betula* and *Pinus*, rather than employing exclusive fire-starting fuels. Alternatively, the low charcoal rate/poor preservation of these vitrified firestarting charcoals could mean that they are frequently only identified to the family level, and thus form the many fragments not identified to genus level. At 350°C, actual changes in prevalence, as expected, negatively correlate to theoretical charcoal production rates; those with high levels of charcoal production reduce in archaeological prevalence when recalibrated. However, given that their proportion is not immutable and based on the number of fragments of that genus alone which are recovered, this correlation is imperfect. Fragmentation bias recalibrations, although changing the proportions in which certain fuels were used, did not change overall charcoal-pollen discrepancies. This suggests that choice still occurred, although not identical choices to those suggested by the raw data alone. Pine, although certainly sought after and used above its environmental availability, was not the only fuel selected for; use of *Juniperus* and *Prunus* declines, and *Rhamnus* and *Quercus* become more common.

When we return to the question of Chapter Five and the primary question of this thesis, the charcoal-pollen discrepancies and thus theorized Neanderthal selection compared to environmental availability, do not greatly alter. If differential charcoal production and fragmentation rates were exclusively responsible for these discrepancies, recalibrated differences should tend towards 0 (in instances with any charcoal present), but this is not the case, as three levels remained identical and some even increased their discrepancy. Given I only recalibrated charcoal, if some genera were only ever present in the landscape (as pollen) but never as fuelwood (so no charcoal), they would remain unchanged by my charcoal production/fragmentation bias recalibrations (see p.221 for where these instances were excluded from recalibrations). Out of 100 possible different genera samples across all sites, 69 are found as pollen only and would be unchanged; however these form only minor discrepancy values anyway, changing the data minimally despite their quantity. This further suggests that differences between the two records are either caused by active Neanderthal choice or by other unknown variables. The additionally recalibrated non-Iberian sites with evidence of charcoal-pollen discrepancies do not tally with the pine-dominant fires of my previous Masters study, despite showing similarly pine-dominated surrounding landscapes. The charcoal records similarly indicate burning of only small proportions of available landscape fuelwoods. However, these non-Iberian Neanderthals frequently select *Juniperus, Quercus* and *Buxus* instead of *Pinus*, although this selection process is still visible. *Quercus* as a fuel, it would appear, was more important for Neanderthals than first thought. Its use was for a good reason, as whilst pine creates large flames and high temperatures, oak burns slower and thus burns less fuel per hour of fire use; their use together would make perfect sense.

When Neanderthal fire is studied independently of pollen records in terms of first/second choice within a fire, *Pinus* remains the most commonly dominant fuel, followed by *Picea/Larix* and *Juniperus*. An average of all Neanderthal fire compositions, irrespective of availability or landscape, shows *Pinus* still being dominant, followed by *Quercus, Juniperus* and *Prunus*. The following chapter deals with whether this prevalence, assuming it stems from active choice, tallies with actual wood qualities, and whether Neanderthals were justified, from a pyrotechnic optimization standpoint, in choosing the fuelwoods they did. I contrast this with Middle Palaeolithic foraging landscapes and strategies from proxy landscapes available in the modern day which most closely resemble their foraging spheres. Looking from a forager's perspective, I also suggest that morphological and other foraging properties of these fuels could have encouraged their selection.

Chapter Nine: Fuelwood Properties.

The previous chapters prove that, despite recalibrations for differential charcoal *and* pollen production, differences still exist between Middle Palaeolithic charcoal and pollen records, within single sites. Whilst taphonomic processes may partially cause this, the almost-universal selections towards pine fuels, selecting them when available and commonly avoiding certain genera, suggest that these trends often represent active selection. Two main hypotheses could explain this selection. The former, discussed in this chapter, is that Neanderthals selected for combustion properties of the fuels themselves. Valuable fuelwood traits can include high burning temperatures, long burning durations, high light outputs, low smoke output (except for meat-smoking), pleasant-smelling smoke, and embers to re-ignite fires from (Abbot et al. 1997, Cardoso et al. 2015, Estigarribia et al. 2023, Ramos et al. 2008, Sahoo et al. 2014, Teklay et al. 2014, Wiafe and Kwakwa 2013). No one fuel could provide all traits, particularly as heat/light (and therefore energy) output at any one time negatively correlates with burning duration, unless calorific values markedly differ. The second hypothesis, discussed in Chapter Ten, is that Neanderthals selected for ease of gathering. Valuable traits here could include straight, easily-bundleable branches of standardised diameter/lengths (Fleuret and Fleuret 1978, Godfrey et al. 2010, Nuberg et al. 2015, Ponce et al. 1991 p.1), and dense woods giving higher burnable masses per unit volume carried (Pote et al. 2006, Shaw 2012).

This chapter consists of two portions; the former looks at hypothetical burning traits of different woods based on measured morphological and chemical properties; calorific value, ash content, density, and wood strengths, noting selection trends and correlating them to optimisation. I found that Neanderthals surprisingly favoured lower-calorie woods. Furthermore, they also favoured quick-burning lower-density woods, although this may have meant higher heat releases per unit time. Lower-calorie and lower-density woods may also produce less charcoal and thus be underrepresented. However, given that hypothetical traits map imperfectly onto actual fire experiences, in the second portion of the chapter I compare wood burning traits from published experiments, focusing on effects (light, heat and burning duration) rather than causes (density, calorific value etc.). Utilising works by Hoare (2020) and Thery-Parisot et al. (2014) on real-life fires, I found that certain traits, such as pinewood burning at high temperatures, are inconsistent, and depend on burning context. I discuss correlations between real-life fire durations and associated ‘charring rate’ in lab-based experiments creating charcoal, and how both of these correlate with wood density. I find that density is a good proxy for charring rate but not for burning duration, due to several additional factors such as wind rate for the latter. Consequently, temperature, light and burning duration of average Neanderthal fires differ for each site, depending on fuel types burnt there, to determine values of each in proportion to pine (=1). Temperature varied least among the sites, and light emitted varied the most. Utilising Hoare’s (2020) burning duration and fuel consumption, I then calculated potential amounts of fuels needed for fires and how this varied depending on fuel genera. I conclude from this that Neanderthals chose certain fuels optimised for slow-burning and minimising fuel use, and others for light output; Neanderthals used both, possibly correlated with latitude, however universally avoiding inferior fuelwoods such as alder, despite their frequent availability. I suggest that Neanderthals particularly avoided fuels which were harder to ignite (despite having other potentially useful properties), and that their selection of easily-igniting fuels could be partially determined by their foraging practices. The examination of this latter hypothesis forms the basis of the next chapter.

I: Independent Traits of Different Fuelwoods.

Fuelwoods vary drastically in many traits, some obvious to Neanderthals, and others underpinning important aspects of their burning qualities. These traits have important practical implications; pioneer studies by Benjamin Thompson (1798) compared heating values of beech, pine and oak, for practical household purposes:

“*Dry pine-wood affords more heat in its combustion than dry beech…. the quantities of heat producible from equal weights of dry oak and dry pine are equal*” (Thompson 1798, p.140)

Other traits such as tensile strength and density, with important implications for construction and tool manufacture, would have been visually obvious even without fire knowledge; traits like calorific value would depend on Neanderthals using woods as fuel rather than for anything else. These traits noted here are independent variables which should partially affect the fires, through heat and light output and burning duration. These are by no means exhaustive independent variables, and exclude branch diameter, length and moisture content, which vary highly from fire to fire, and even stand to stand within the same fuelwood genus.

Consequently, my calculated burning trait values for each genus form means of wide ranges. These ranges are so wide because they represent genera composed of many different species with slightly varying values. *Quercus* charcoal could plausibly have come from 22 European species; most commonly *Q. robur* (English oak), *Q. ilex* (Holm oak) or *Q. petraea* (Sessile oak) – although *Quercus deciduous* and *Quercus evergreen* are frequently distinguished. Thus we cannot assume any one species; by creating means, we find average traits of each genus, admitting however the huge potential variety, indicated by the range.

Within a species, wood traits vary drastically, due to age, climate, health, part of the tree, season, and even research procedures. Green wood is naturally denser than dry wood; and likewise has lower net calorific values as more water must be evaporated pre-combustion. Even within annual sap cycles, traits change; Nunez-Regueira et al. (1996) note distinct annual calorific fluctuations, being highest around summer blooming periods and lowest in wet springs. This is the same for other traits; within the same *Sorbus* specimen, Nunez-Regueira et al. (1997, p.112) noted a 16.9% change in moisture content, 20kg/m^3 difference in density and a 1.87% ash content difference. Given we do not know at which season Neanderthals occupied most sites, we cannot account for annual fluctuations, and must create averages.

Thirdly, amounts of literature on each genus varies immensely, due to differing interest in different genera. Some such as *Pinus* have well-researched density and strengths for construction purposes; others such as *Quercus* are useful biofuels (e.g. Fang et al. 2011). Others however, including *Ilex*, are disregarded either because or rarity or perceived poor qualities. Generally, high-ranking genera in each trait have most papers published on them, although this is not universal – only Bhatt and Todaria (1992) note *Ilex*'s high calorific value, because it is rarely exploited. Genera with many papers on them are more likely to cover all relevant species, all states/types of wood, and to have accurate average data.

Density, Calorific Value and Ash Content values have been previously presented in Chapter Seven (Tables 7.11-7.13), pp.187-190. Corresponding Fuel Value Indices (FVIs) and mechanical traits for these genera are presented here.

As calorific values per kg and densities are known, calorific value by volume (kJ/cm^3) was derived for each genus, to show energy derivable by volume, as Neanderthal fuelwood gathering may have been limited more by bulkiness than weight on foraging trips. FVIs were calculated using the following calculation:

$$Fuel\,Value\,Index = \frac{Calorific\,Value\ \times\ Density}{Ash\,Content}$$

FVIs rank wood fuels for industrial or private purposes, taking calorific value by volume and unburnable ash content into account (first used by Purohit and Nautiyal 1987; see Goel and Behl 1996, Deka et al. 2007 for more details). Other authors (e.g. Ojelel et al. 2015) also incorporate wood moisture content by modifying to the following formula:

$$Fuel\,Value\,Index = \frac{Calorific\,Value\ \times\ Density}{Ash\,Content\ \times\ Moisture\,Content}$$

However, whilst minimum moisture contents are relevant for industrial purposes, we do not know in what state Neanderthals burnt their wood, so this is excluded from my equation. Given varied methodologies for calculating FVI, from multiple datapoints, I calculated my own values using the first formula, rather than using published material (Table 9.1).

Table 9.1: Calculated FVI of all studied genera. It is interesting to note that many preferred genera, such as Acer, Pinus and Quercus, have relatively low FVIs, and less-used fuels such as Alnus and Pistachia have higher values. This shows how FVI imperfectly translates to actual fuel use. Pinus and Quercus are valued for being dry and easy-to-burn; Alnus is too smoky for regular use, and Pistachia is very green when cut. Erica would be optimal, if its spindly branches were not impossibly to carry.

Genus	**Fuel Value Index (FVI)**	**Genus**	**Fuel Value Index (FVI)**
Olea	3.08	*Salix*	7.11
Tamarix	3.72	*Prunus*	7.30
Corylus	3.76	*Hippophae*	7.91
Acer	4.19	*Fraxinus*	9.11
Pistachia	4.23	*Alnus*	9.86
Pinus	4.93	*Ulmus*	10.91
Taxus	5.52	*Viburnum*	10.95
Sorbus	6.11	*Betula*	11.83
Rhamnus	6.38	*Arbutus/Ilex*	12.63
Quercus	6.52	*Erica*	17.45
Buxus	6.67	*Juniperus*	17.46
Castanea	7.04	*Phillyrea*	28.23

I.I: Wood Strengths.

Table 9.2: Different wood strength moduli for 20 genera, taken from published literature; all citations are included.

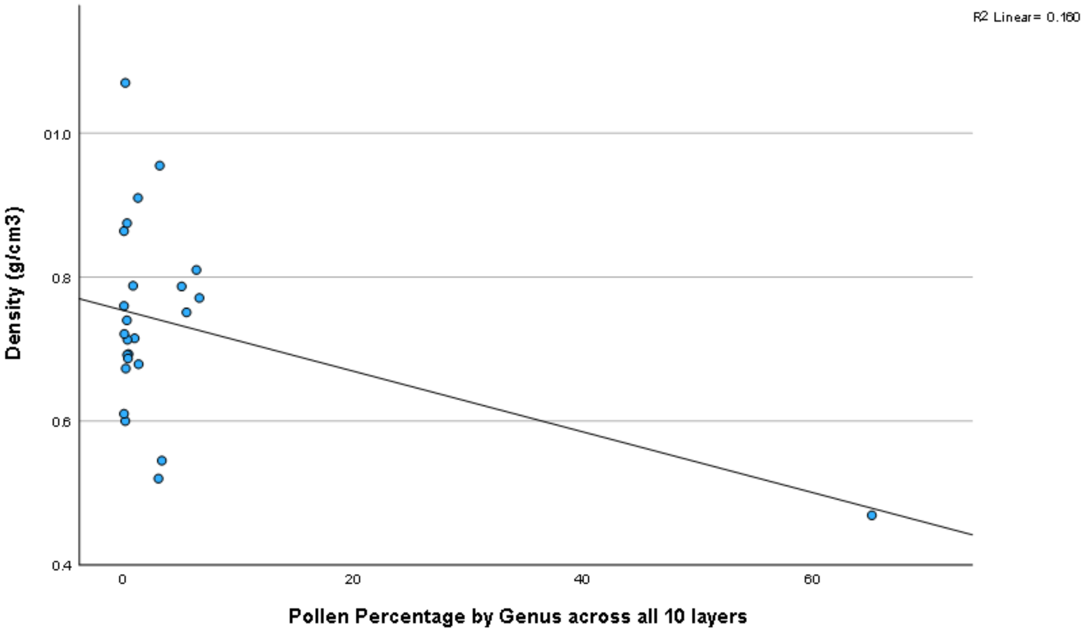
Genus	Compressive Strength (MPa)	Mean	Bending Strength (MPa)	Mean	Modulus of Elasticity (MPa)	Mean
Acer	15.5, 26, 27.5, 29, 33, 35.3, 43.1, 45.5, 46, 49, 49, 50, 51.5, 53, 55, 55.2, 55.6, 57, 62, 72, 75.187, 83	48.56	50, 58, 66, 85, 88.5, 95, 95, 102, 108, 110, 120, 135, 135.52, 140, 148, 162	106.13	12216.621, 12392	12304.41
Cionca et al. 2008, Korkut et al. 2008, Molinski et al. 2016, Niklas 1999, Niklas and Spatz 2010, Sedlar et al. 2017, Sonderegger et al. 2013						
Alnus	21.7, 32.82, 33.52, 34.05, 38.46, 38.98, 39.11, 39.65	34.79	49, 53.4, 54.3, 54.59, 61.69, 62.89, 64.39, 68.7	58.62	5850, 5880, 7040, 7400, 8600, 8800, 9500, 9500, 10319, 10600	8348.9
Kiaei 2013, Milch et al. 2016, Molinski et al. 2016, Niklas and Spatz 2010, Usta et al. 2014						
Arbutus	61	61	135	135	--------------	--------
Navarro et al. 2007, Voulgaridis and Passialis 1995						
Betula	19.2, 20.4, 20.5, 21.3, 26.3	21.54	----------	---------	8108, 8187, 8483, 10218, 10919, 11404, 11539, 11659, 11739, 12668, 13269, 13450, 14000, 16887	11609.29
Antons et al. 2018, Boruvka et al. 2019, Cavus 2020, Dunham et al. 1999, Erdene-Ochtir et al. 2020, Molinski et al. 2016, Niklas and Spatz 2010						
Castanea	26.7, 21.8, 34.04, 46.9, 47, 48.56, 49, 51, 52, 54, 62.9, 70.61	47.04	55.96, 71, 79.49, 87, 88, 88, 93.16, 94.5, 98, 113.5	74.08	5356.74, 6708.6, 7535.2, 8421.8, 9379, 9757	6150.17
Gunduz et al. 2009, Marini et al. 2021, Rubiales et al. 2011, Stokes and Mattheck 1996, Thaler et al. 2014, Vazquez et al. 2015, Yapici and Ulucan 2012						
Corylus	55.64, 74.74	65.19	78.66, 115.44	97.05	-------------	----------
Korkut and Hiziroglu 2009						
Erica	56.4, 58.9	57.65	49.1	49.1	------------	-----------
Voulgaridis and Passialis 1995						
Fraxinus	23.9, 27.2, 29.1, 51, 54.92, 70, 72, 77, 78, 80, 85	58.92	66, 118, 121, 124.31, 125, 134, 137.29, 140, 146, 147, 164	129.33	11557, 11622, 11931, 12011, 12371, 12623, 13130, 13358, 13518, 16281	12840.2
Hofmann et al. 2012, Mantanis and Birbilis 2010, Molinski et al. 2010, 2016, Niemz et al. 2014, Niklas and Spatz 2010, Rubiales et al. 2011, Stokes and Mattheck 1996						
Juniperus	35.65, 50, 50.99	45.55	17.3, 24.01, 27.04, 36.65, 40.1, 42.11, 44.65, 45.05, 49, 53.92, 54.55, 55.73, 57.03, 57.17, 58.44, 58.44, 60.59, 61.57, 63.65, 64.49, 64.49, 80, 81, 84, 84, 102.97, 104, 113	58.09	2739.28, 3550, 3561.37, 3744.2, 3869, 3948, 3948.48, 4300, 4330, 4450, 4480, 4550, 4603.64, 4610, 4629.8, 4650, 4709, 4800, 4906, 4915, 4915.96, 5150, 5153, 5344, 7400	4530.27
Bjurhager et al. 2013, Hanninen et al. 2012, Kiaei et al. 2015, Miyamoto 2017, Miyamoto et al. 2018, Rubiales et al. 2011						

Genus	Compressive Strength (MPa)	Mean	Bending Strength (MPa)	Mean	Modulus of Elasticity (MPa)	Mean
Olea	48.8, 62.87	55.84	105	105	-------------	-----------
Niklas and Spatz 2010, Voulgaridis and Passialis 1995						
Phillyrea	57.1	57.1	-----------	---------	-------------	------------
Voulgaridis and Passialis 1995						
Pinus	13.9, 16.9, 17.4, 17.7, 18.5, 18.8, 19.1 19.1, 19.4, 21, 21.9, 23.4, 25.5, 27.3, 31.8, 33, 36.68, 37.4, 46.55, 46.58, 49.9, 50, 51, 52.59, 56.6, 59.713, 69.38, 69.68, 72.99, 74.41, 75.23, 76.03, 80.78, 84.54, 86.87	43.47	23.6, 23.74, 27.5, 28, 30.76, 34.93, 36, 38, 38, 41, 41, 41, 44, 63, 64.81, 65, 66, 69.13, 69.6, 77.79, 80.23, 81.87, 83, 83.17, 84.31, 84.85, 86, 86.41, 93.4, 93.64, 96.76, 97.1, 97.76, 98.07, 138.026	64.67	909.45, 969.49, 1046.18, 1398.1, 1472.776, 1504.02, 8000, 8444.8, 8894.24, 8900, 10735.53	4752.24
Aleinikovas and Grigaliunas 2006, Antons et al. 2018, Bjurhager et al. 2013, Cionca et al. 2008, Durhmaz et al. 2019, Korkut et al. 2008, Miyamoto 2017, Miyamoto et al. 2018, Niklas and Spatz 2010, Rubiales et al. 2011, Stokes and Mattheck 1996, Ulker et al. 2012, Yildiz et al. 2004						
Pistacia	52.5	52.5	105.2	105.2	------------	-----------
Voulgaridis and Passialis 1995						
Prunus	50.2, 51.6, 52.94, 53.55, 53.9, 54.01, 55.16	49.9	64, 81.88, 111.2, 113.1, 114.5, 116.2, 119.3	102.88	6569, 8650, 11341, 11638	9549.5
Cavus 2020, Niklas and Spatz 2010, Nocetti et al. 2010, Pavlovics et al. 2009						
Quercus	23.5, 27.6, 28.5, 28.7, 29.4, 29.4, 36.3, 37.2, 42, 42, 42, 43.1, 48, 51, 54, 55, 55.3, 57, 57.4, 58.84, 59.4, 60, 60.8, 60.8, 61, 61, 64, 64, 64, 64.72, 65, 65, 67, 70, 71.81, 72.95, 74.76, 75.15, 75.5, 83.3, 84.3, 84.3	56.07	53, 53, 58.8, 58.8, 59, 60, 65, 70, 72, 74, 75, 75.2, 78, 86.9, 88, 92.1, 92.1, 95.12, 95.8, 96.5, 98, 98, 98.6, 100, 101.8, 105, 106.2, 106.89, 108, 108, 108.2, 108.8, 110, 110, 110, 110, 111.43, 117, 117.7, 120, 120, 124.8, 134.9, 135.9, 140, 146.1, 152, 153, 153	100.24	9200, 10000, 10200, 10300, 10500, 10500, 10600, 10600, 10830, 11000, 11300, 11500, 11600, 11700, 11700, 11820, 11840, 11848, 11900, 11910, 12500, 12500, 12700, 13000, 13000, 13100, 13200, 13200, 13500, 13900, 14500, 14500, 14600, 14600, 15700, 15700	12251.33
Kretschmann and Green 1999, Merela and Cufar 2013, Molinski et al. 2016, Niklas and Spatz 2010, Percin et al. 2015 Rubiales et al. 2011, Voulgaridis and Passialis 1995						
Salix	13.7, 14.7, 14.8, 26.9, 26.9, 27.1, 28	21.73	31, 31, 35, 36, 54, 54.6, 62.05, 63.1, 72.1, 75.93, 84.36, 85.35, 89.61, 111.02, 115.34, 116.83, 126.39, 131.33, 140.26, 148.91	83.21	1566, 1762, 1847, 1938, 1941, 2006, 2014, 2051, 2059, 2132, 2168, 2170, 2205, 2214, 2255, 2314, 2401, 2453, 2480, 2526, 2571, 2631, 2742, 2751, 2857, 2988, 3027, 3179, 3260, 3328, 3358, 3413, 3458, 3641, 3734, 3735, 3863, 4011, 4116, 4147, 4222, 4284, 4478, 4559, 4692, 4826, 4856, 5004, 5060, 5196.05, 5293.24, 5520, 5861.68, 5955.03, 6293.03, 6800.68, 7057.11, 7335.98, 7674.38, 8375.85, 8640.28, 8805.43, 9348.07, 9482.7, 13540, 15840, 15930	4540.93
Leclercq 1997, Niklas and Spatz 2010, Sedlar et al. 2017, Vargas et al. 2012, Wiaderek and Waliszewska 2010, Zhou et al. 2017						
Sorbus	53.012, 61.017	57.01	88.331, 123.079	105.71	9255.81	9255.81
Keskin et al. 2013, Korkut and Kudakci 2009						

Genus	Compressive Strength (MPa)	Mean	Bending Strength (MPa)	Mean	Modulus of Elasticity (MPa)	Mean
Tamarix	11.77, 32.26, 40.9, 47.37	33.08	88.5, 98.07	93.29	7533, 8336.34	7934.67
Khan and Siddiqui 1984, Mantanis and Birbilis 2010						
Taxus	48, 54, 57, 58, 61, 62, 63, 68	58.88	83, 85, 92, 100, 105, 118	97.17	6200, 6200, 7000, 7700, 9700, 9700, 10100, 10300, 10500, 11500, 12000, 13100, 13700, 14300, 15700, 16900, 17400	11294.12
Bjurhager et al. 2013, Keunecke and Niemz 2008, Keunecke et al. 2007, 2008, 2009, Molinski et al. 2016						
Ulmus	16.9, 18.7, 30.4	22	40, 44, 68, 91.5, 103, 106, 111	80.5	9211, 10971, 11082, 12193	10864.25
Niklas and Spatz 2010, Santini et al. 2004						

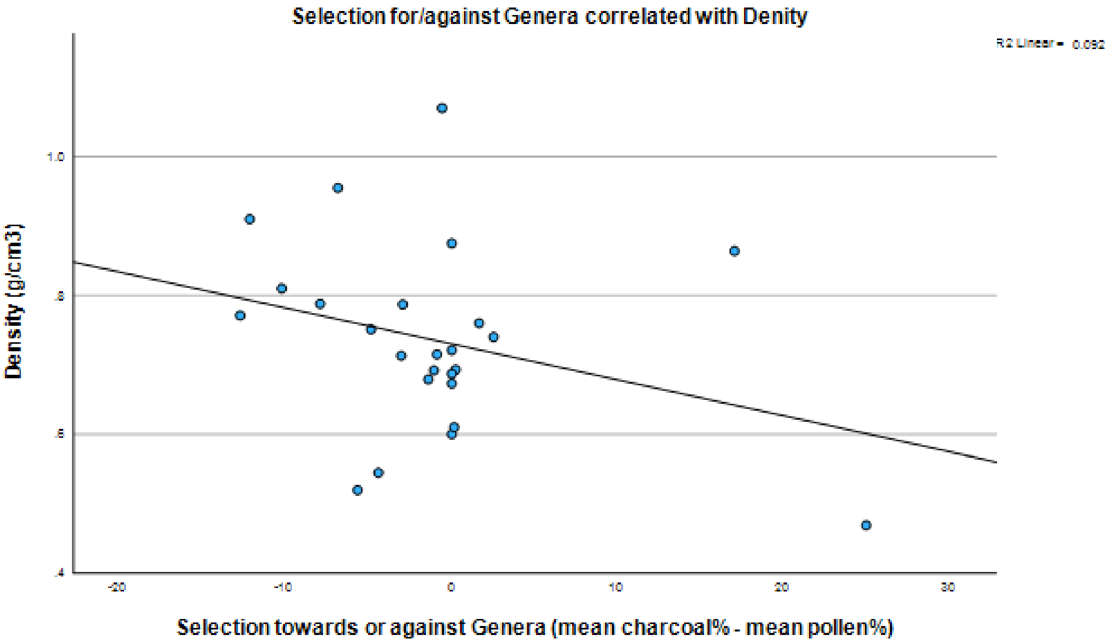
I.II: Data Trends.

When correlating Neanderthals' selection with these traits, several trends emerged as seen in the graphs below. When looking at 'natural' environments (pollen), to see whether natural trends could skew the anthropogenic data to forced conclusions (e.g. natural trends towards dense wood suggesting selection of dense wood even when collecting randomly under the Principle of Least Effort), few trends were apparent – see Appendix Seven, Graphs A14-A20. Genera with weak bending strengths and low moduli of elasticity were slightly more environmentally-common, but this trend was statistically insignificant. The only statistically significant trend (p = 0.049) was that dense woods were environmentally-rarer (see Graph 9.1).



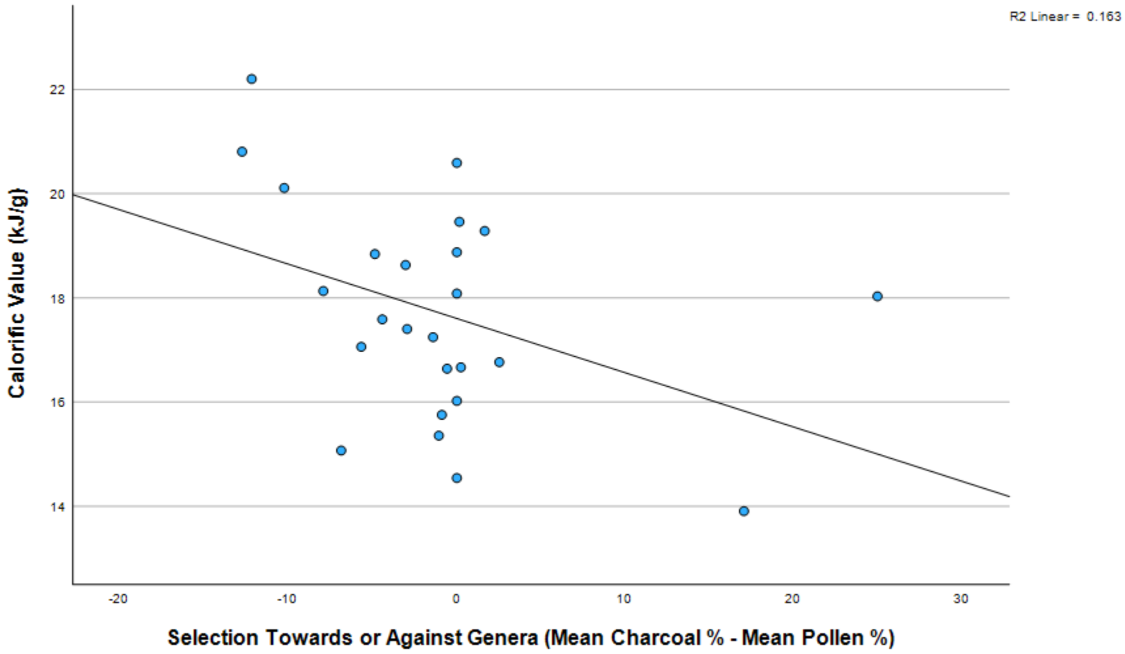
Graph 9.1: Incidence of wood types in the landscape as a function of density (R2 = 0.160). This shows that low-density woods are commoner in the landscape (p = 0.049), though this result is very dominated by the properties of pine.

Pinus pollen predominates (mean = 61.50%), a less dense wood that could have naturally have influenced Neanderthals towards selecting less dense woods under random selection, irrespective of them consciously selecting for this trait. The graphs below plot a ‘selection index’ on the x-axis, defined as the fraction of a genus as charcoal minus that as pollen. This uses the formula from p.219, and uses recalibrated values for both charcoal and pollen. A statistically-insignificant (p = 0.141) negative trend of selection index as a function of density (Graph 9.2), suggests some small preference for less-dense woods.

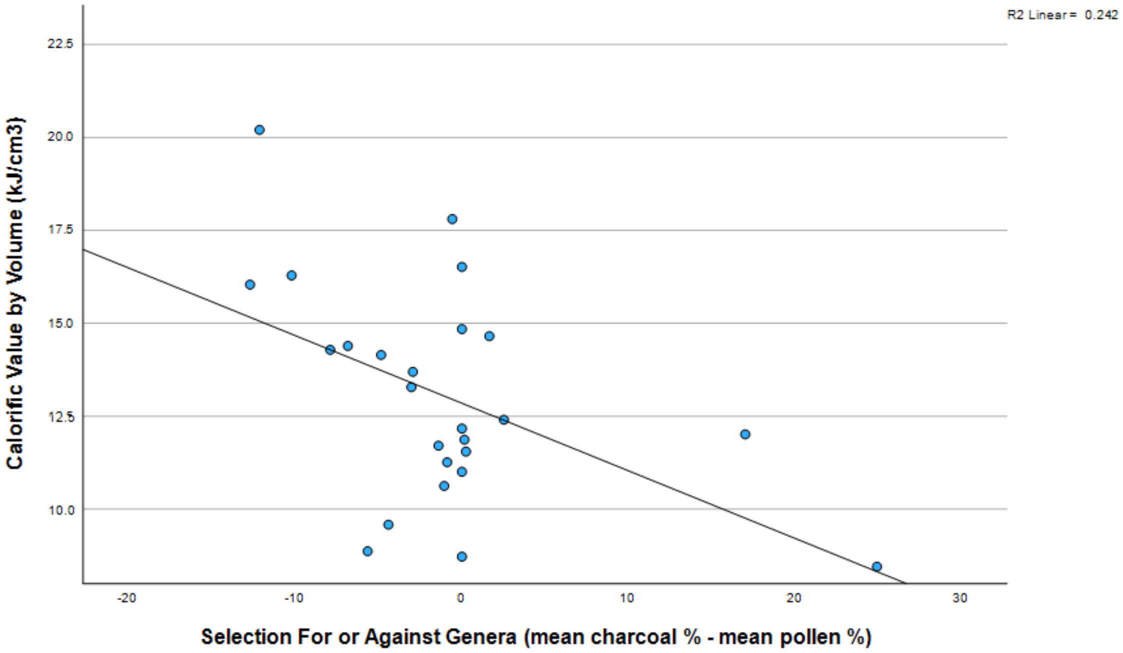


Graph 9.2: The selection index as a function of density suggests that Neanderthals preferred less-dense woods for burning. This is statistically insignificant (R2 = 0.092, p = 0.141), but suggests that lower weights per unit volume carried may have been important to these hunter-gatherers.

Contrary to expectations, preferred fuelwoods actually had much *lower* calorific values than those rejected, a strong negative correlation significant to p=0.05 (0.045) – see Graph 9.3. Precisely the opposite is expected, as calorifically-higher wood burns at higher temperatures and/or for longer, thus requiring smaller fuelwood quantities. This trend is likewise borne out when looking at calorific value by volume, for which the trend is stronger and more statistically significant (p = 0.013, Graph 9.4). There are similar non-significant negative correlations suggesting selections towards lower compression strength, bending strength and elastic moduli (see Graphs 9.5-9.7).



Graph 9.3: The woods which Neanderthals strongly selected for were generally less calorifically valuable (R2 = 0.163, p = 0.045). Selection for this trait is unlikely to have been deliberate.



Graph 9.4: Woods which Neanderthals strongly selected for also had the lowest calorific value by volume (p = 0.013), as a consequence of selecting for low-density and low-calorifically-valuable woods (R2 = 0.242).

I.III: Correlations of Wood Traits with Natural Environments.

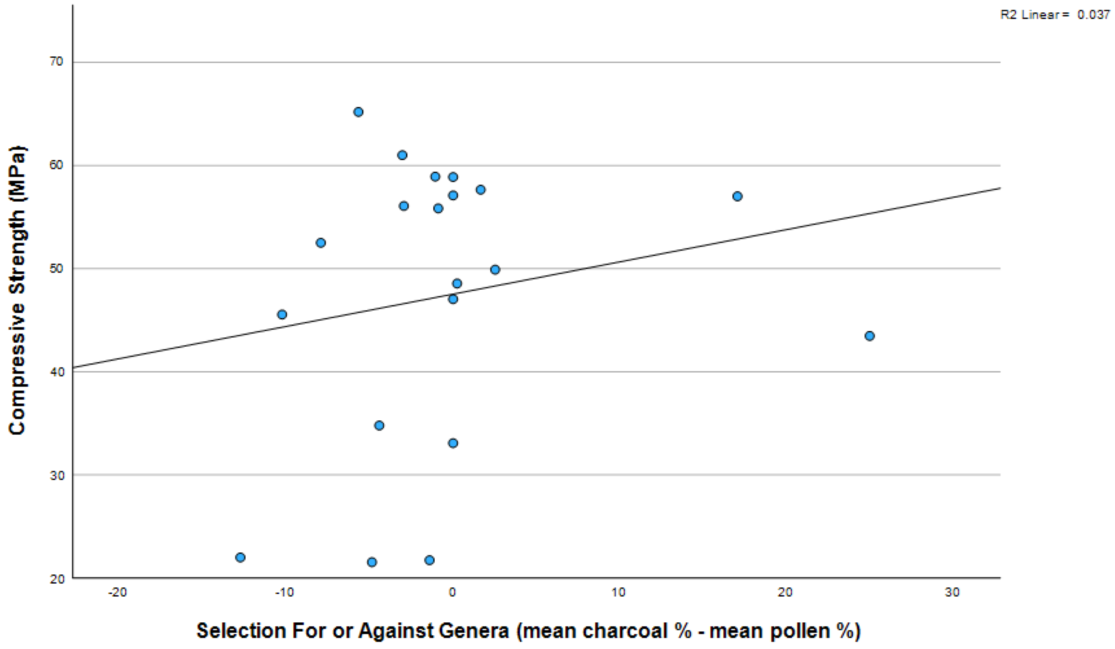
Table 9.3: Comparing whether Middle Palaeolithic environments happened to contain trees with particular traits, which could artificially suggest apparent choice for those traits even if random selection was practiced. Only density is significant, with less-dense trees more common in the landscape.

Correlation with Pollen %	**Pearson Correlation**	**Two-Tailed Significance**	**Statistically Significant?**
Ash (%)	-0.056	0.791	No
Density (g/cm^3)	-0.397	0.049	Yes
Calorific Value (kJ/g)	0.085	0.687	No
Calorific Value by volume (kJ/cm^3)	-0.287	0.164	No
Fuel Value Index	-0.124	0.554	No
Compression Strength (MPa)	-0.141	0.552	No
Bending Strength (MPa)	-0.367	0.134	No
Modulus of Elasticity (MPa)	-0.411	0.145	No

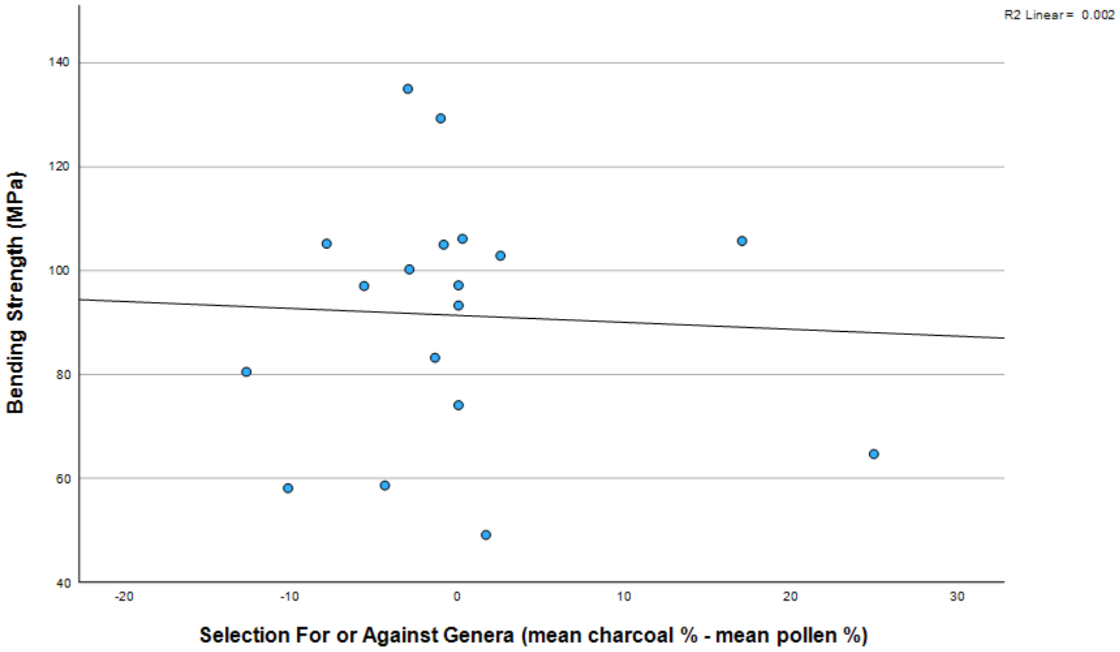
I.IV: Correlations of wood traits with Neanderthal selection.

Table 9.4: comparing which fuelwood traits Neanderthals selected for and against. Neanderthals seemed to select for woods with low calorific values, and low calorific values by area.

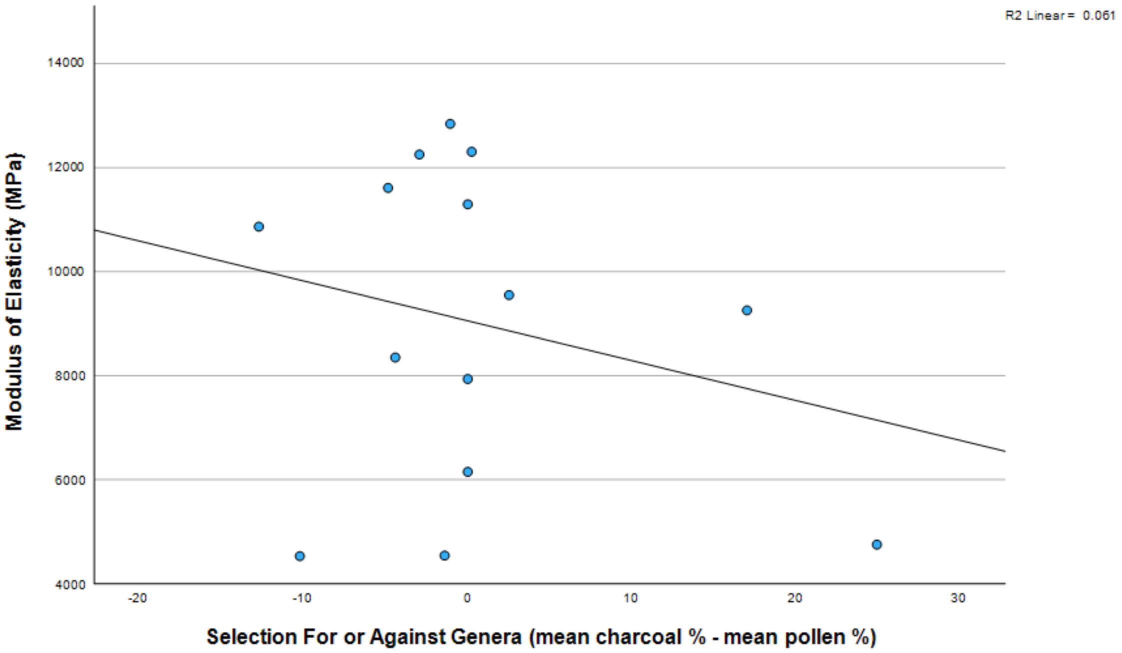
Correlation with Neanderthal selection (mean charcoal % - mean pollen %)	**Pearson Correlation**	**Two-Tailed Significance**	**Statistically Significant?**
Ash (%)	0.019	0.928	No
Density (g/cm^3)	-0.303	0.141	No
Calorific Value (kJ/g)	-0.404	0.045	Yes
Calorific Value by volume (kJ/cm^3)	-0.492	0.013	Yes
Fuel Value Index	-0.219	0.316	No
Compression Strength (MPa)	0.195	0.410	No
Bending Strength (MPa)	-0.058	0.818	No
Modulus of Elasticity (MPa)	-0.246	0.396	No



Graph 9.5: Neanderthals appeared to choose harder-to-chop (higher compressive strength) woods (p = 0.41, R2 = 0.037); this is unlikely to be deliberate however. They were unlikely to have chopped trees down, rather bending and breaking branches instead, so compressive strength of wood may not have affected how they gathered it.



Graph 9.6: Neanderthals also chose to burn easier-to-snap (lower bending strength) woods (p = 0.818). The correlation here is more tenuous however, and the correlation not as strong (R2 = 0.002).



Graph 9.7: Neanderthals also burnt less pliable woods (ones with a lower Modulus of Elasticity) (p = 0.396). Not all genera had been tested for MoE however, and the correlation is not strong (R2 = 0.061).

II: Discussion.

Despite limited evidence, certain interesting trends have emerged. Selection against high-calorie woods may be explained either as active choire or an artefact of preservation. Higher calorific values cause potentially hotter fires as well as more complete combustion. Although some genera have particularly high-calorie extractives (e.g. conifer resins), nevertheless high-calorie woods are generally those with higher proportions of extractives to structural components. Thus high calorie woods have lower proportions of unburnable (charcoalifiable) structural cellulose – and vice-versa for low-calorie woods. Low-calorie woods may be overrepresented as charcoal because they have more non-burnable components which survive as charcoal. They are also more likely to burn at lower temperatures favouring charcoal production (see Chapter Seven, p.177). Furthermore, although *Pinus* has only moderate calorific values, it has extremely high extractive resin calorific values of 45kJ/g (Susott 1980) which is uncommon in other lower-calorie woods.

The other option is that these woods were actively selected for. Neanderthals would not have chosen lower calorie woods for that function, as they may not have even understood or known about heating values; some other fuelwood trait, correlating with low calorific values, compensated for lower energy outputs. One of these is of course density – *Pinus'* notably low density of course further drives calorific values per unit volume down. However, low-density wood is far lighter and more portable than denser wood. Neanderthals judging fuel value by volume instead of weight would select lighter fuelwoods. Secondly, less dense wood is far more combustible than denser wood, burning faster and hotter – when dry, air-filled wood interstices encourage combustion. Less dense wood also tends to be more completely combusted and thus creating less charcoal; they might have dominated fuel inventories even more than indicated by charcoal records.

Lower densities, with fewer structural wood components per given area, also contribute to weaker strengths. However, calorific values present opposite trends. High calorie woods containing many extractives must have proportionally fewer structural components. Compressive strength, referring to how much force wood can sustain when compressed, is only relevant if Neanderthals cut firewood using lithic axes. Bending strength (or Modulus of Rupture - MoR), referring to how much bending force wood can sustain, is particularly relevant to bending and breaking side branches off trees for fuel without tools. Modulus of Elasticity (MoE) relates to how much branches can be stretched; ones with lower MoE are also more easily bent and suggests lower strengths, although the two properties are not directly linked. Nonetheless, more pliable branches can generally be more easily broken off, or fall off naturally. In general, weaker wood may have been used for firewood. It is less useful for other functions, either structural or as tool hafts, and thus burning this inferior wood preserves superior wood stocks. A high MoE is advantageous when wood beams are under structural pressure, providing that other strengths are still high, so low-MoE wood would not have been used structurally. There is no evidence however that Neanderthals used structures, but wood may have been used for demarking social boundaries within camps, and for tool hafts.

Weaker wood is easier to break off trees. Different trees have different rates of dead branch shedding; some lose them easily (*Acer, Betula, Fraxinus, Prunus* – Millington and Chaney 1973, Oettel et al. 2023), other trees retain them for longer (*Juniperus, Quercus, Pinus* – Ibid). Deadwood loss rates are of course not only related to these various strengths; different trees respond differently in terms of shutting off sap to dead branches, and accelerating branch loss by growing protective tyloses. Bending strength especially affects wood loss in storms; 23-29% of tree loss is caused by storms in lowlands, and 41-47% in mountainous regions (Christensen et al. 2005). In 1987, storm damage doubled English deadwood stocks overnight, gaining 23m^3/ha of deadwood (Kirby et al. 1998). Certain genera like beech are particularly prone to wind damage, with storms causing 94% of their deadwood (Mountford 2002) – though no genus which Neanderthals exploited is quite so prone as this. In Palaeolithic environments, mammoths may also have created deadwood stocks. Modern elephants frequently damage trees to access edible leafy branches (Coetzee et al. 1979, Morrison et al. 2016); up to 7% of certain tree genera can be killed through such breakages (Jacobs and Biggs 2002). Whilst we do not know how mammoths foraged, they were a plentiful prey species, comprising at least 20,000 individuals in the Middle Palaeolithic (Palkopoulou et al. 2013). Neanderthals would have followed and hunted mammoth herds, and if combining hunting with firewood foraging, they would have encountered mammoth-damaged trees. Dense, covered woodlands could also have been chosen for ambushing mammoths, alongside plains and cliffs. Other species including beavers or deer also strip bark (Jones et al. 2007), providing access areas for Neanderthals to further exploit.

Weaker woods are proportionally more affected by these factors, and create more deadwood. Neanderthals may have recognized and chosen easy-to-break wood, or simply chosen randomly from more abundantly-available weaker deadwood pools. Distinguishing between these behaviours is extremely difficult. Whilst researchers discuss quantities of deadwood created by various genera (e.g. Chabal and Heinz 2020, Korkut et al. 2009), these are frequently for commercial monospecific forests. Unmanaged forests vary immensely due temporary deadwood gluts from storms (or stormless years causing deficits), and different moisture contents and organism communities causing different deadwood decay rates.

Deadwood also relates to growth rate, and how quickly new branches are created. This depends on climatic conditions and local ecology and has been clarified in several modern studies (e.g. Bujoczek et al. 2018, Oettel et al. 2023, Wilson and McComb 2005). However, Palaeolithic landscapes are less well understood and cannot be modelled using modern analogies. Nonetheless *Pinus* and *Sorbus*, genera strongly selected towards, are very quick-growing. Slower-growing genera like *Juniperus* appear to be rejected – though how much tree growth rate relates to limb regeneration rate is unclear. This trend may mimic *H. sapiens* being forced to select faster-growing species during the Broad Spectrum Revolution (BSR - Flannery 1969) once they reached population carrying capacity with current foraging practices. Neanderthals may not have actively thought about fuelwood regrowth rates. However, the BSR model supposes that humans were previously at their current population carrying capacity – Neanderthals were not anywhere near those levels. Likewise, the BSR applies only to very common technologies (such as hunting) leading to environmental depletion – Neanderthals may not have used enough fuelwood at population levels to cause such issues.

Ash production and density are seemingly unconnected to Neanderthal selection. Fuel Value Index, ratioing the two former properties, is naturally also uncorrelated. Palaeolithic palimpsests blurs many individual fire features and events, giving us only averages. Were Neanderthals unselective for these traits at all, or did they alternately select high/low ash or density woods for different functions, on one fire or different ones, but all recognition of individual function has been effaced? The only detectable trends are where one end of a trait's spectrum is noted (e.g. low calorific value). These uncorrelated traits may suggest alternating priorities among different Neanderthal individuals, or specialist fires for different purposes (perhaps running concurrently), or possibly selection for entirely different traits - or none at all. However, it is important to remember that traits are not what Neanderthals would have considered, but rather the *effects* of different fuelwoods. If correlations between traits and effects were perfect, traits would be perfect proxies, but as it is, real-life experiments in the next section better indicate the effects of different fuelwoods.

III: Burning Qualities of Different Woods.

Many studies discuss properties of different fuels; top temperatures achievable in fires, durations or rates of burning, light emitted, etc. However, these studies use different methodological procedures and are not immediately standardisable. As well as fuel type, other important factors influencing fire events include hearth construction or style, and ambient temperatures and wind conditions. Caves are slightly more standardised in temperature than exterior conditions, due to buffering effects of the walls (Smithson 1991) and less prone to wind and gusts. If Neanderthals however constructed their fires near entrances or in more exposed rockshelters, these fluctuations would still be important. For instance, one set of Hoare's (2020) fires utilised 7kg of fuel in 30cm-diameter fires, whilst another set used 35kg of fuel in 1m-diameter fires, naturally creating very different results. Similarly, laboratory studies on charring rates burnt woods at different temperatures, with different samples masses or volumes. Only within a single study (or in Hoare's case, a substudy) burning under identical conditions, can different fuelwood genera be distinguished as having different properties. 30cm fires best represent smaller hearths in Abric Romani, and the majority in Shanidar Cave – see Figure 1 below.

Figure 9.1: A small 30cm fire in Shanidar Cave, 2023 excavation. Photograph: Graeme Barker.

Within each study, I have categorised each genus in proportion to each other one, centred around the value of *Pinus* = 1

This is because pine is the most common Neanderthal fuel, and is included in almost all these studies. Thus, if theoretically pine burnt at a top temperature of 500°C, oak at 400°C and birch at 750°C, then *Quercus* = 0.8, *Pinus* = 1, *Betula* = 1.5.

This is only a relative value between the genera, irrespective of actual burning temperatures. This is because, whilst differences between genera under identical conditions are due to innate genera-specific differences in the woods, differences between one genus in experiment A, and another genus in experiment B, vary due to methodological constraints. However, the proportions between the genera should remain constant. Means are created of these values normalised to *Pinus*, which are found to range 0.81-1.04 for temperature, 0.58-1.63 for burning duration, 1-1.35 for charring rate and 0.44-2.55 for light emitted. Original calculations from Hoare's and Thery-Parisot's papers are in Appendix Six (Tables A148-A160).

III.I: Top Temperature Attained.

Table 9.5: 12 genera ranked in proportion to pine for the top temperature which can be attained in fires composed only of that genus.

Genus	**Proportions compared to *Pinus* = 1**	**Mean Proportion compared to *Pinus* = 1**
Populus	0.805	0.805
Alnus	0.7483, 0.8978, 0.9814	0.8758
Carpinus	0.8957	0.8957
Larix	0.8229, 0.925, 0.9884	0.9121
Fraxinus	0.8668, 1.0125, 1.0186	0.9660
Picea/Larix	N/A	0.978
Quercus	0.7946, 0.9977, 1.0349, 1.092	0.9796
Pinus	N/A	1.00
Betula	0.8844, 1.0105, 1.0295, 1.0866	1.0028
Fagus	0.9707, 1.0221, 1.0318	1.0082
Olea	1.0204	1.0204
Corylus	1.0374	1.0374
Picea	0.8549, 1.1136, 1.1628	1.0438

(After Hoare 2020, Thery-Parisot et al. 2014), Mean = 0.9570.

Top temperatures here reflect fire peaks rather than temperature profiles over time. Genera quickly releasing heat and gaining higher peak temperatures, do not necessarily release most energy and therefore heat overall. Furthermore, some fuels may release higher proportions of energy as light rather than attaining high temperatures, or vice-versa. However, top temperatures are more often measured in fires than overall heat output, primarily because it is much easier to note top readings than to calculate overall outputs, especially when temperatures fluctuate. High peak temperatures are also valuable; fires may be most risky at that point, but can quickly heat enclosed areas such as caves, or provide high temperatures required for bone burning.

The results here are generally as expected; lower peak temperatures of wetter softwoods such as *Alnus* and *Populus* correlate with low densities and high moisture contents. Moisture content is a key burning attribute, which I took into consideration (Chapter Six, p.167). *Pinus*, although often regarded as hot-burning (albeit fast-burning); has (shorter) peak temperatures scarcely higher than *Quercus*, a fuel regarded by some as much superior. Furthermore, dichotomies in values between *Larix* (0.9121) and *Picea* (1.0438), means that combined *Larix/Picea* charcoal values must be viewed carefully. However, maximum temperature varies much less than other fire criteria, suggesting that fuel type has less impact here.

Maximum temperatures do not correlate with the wood’s calorific value (Appendix Seven: Graph A21); higher value fuels, as measured in laboratories, correspond to overall heat output over time instead of higher peak fire temperatures. This is due to different rates of heat output from density and varying branch morphologies, so that the wood’s calorific value is only part of the equation. Maximum temperatures likewise do not correlate with wood-to-charcoal conversion rates (Appendix Seven: Graph A22). Hotter-burning fuelwoods might produce less charcoal, both because more is burnt up to attain this temperature, and because less charcoal is produced at very high temperatures compared to lower ones. However, this is not the case; maximum temperature values are very similar, suggesting that peak temperatures for charcoalification are similar, and low 700°C conversion rates show that minimal charcoal is created at such high temperatures anyway. Temperature increases above 700°C, which most of the peak temperatures are, does not change charcoal outputs, suggesting that duration of post-peak lower-temperature heating is more important in creating charcoal.

III.II: Duration of Combustion.

Table 9.6: 12 genera ranked in proportion to pine for how long they burn (higher numbers = longer burning durations) in fires with only that genus as fuel.

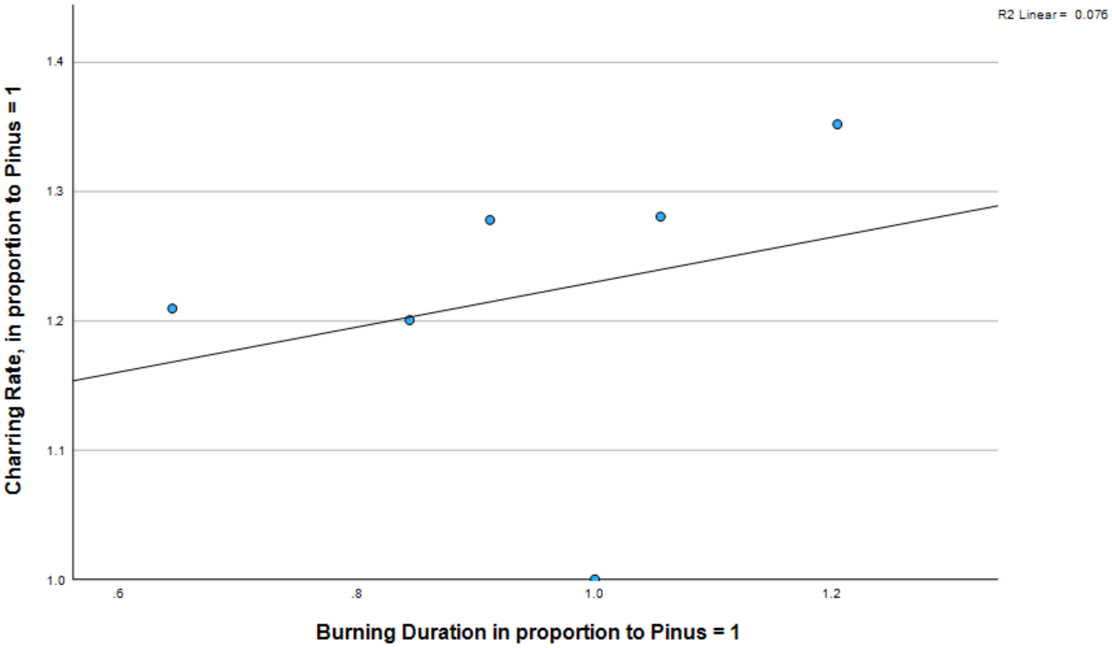
Genus	**Proportions compared to *Pinus* = 1**	**Mean Proportion compared to *Pinus* = 1**
Alnus	0.4615, 0.5556, 0.7143	0.5771
Picea	0.4444, 0.7179, 0.7714	0.6446
Picea/Larix	N/A	0.8362
Betula	0.6296, 0.7692, 0.9714, 1.0067	0.8442
Fagus	0.7778, 0.8718, 1.0857	0.9118
Corylus	0.962	0.962
Populus	0.9843	0.9843
Pinus	N/A	1
Larix	1.0277	1.0277
Olea	1.0291	1.0291
Fraxinus	0.8718, 1.037, 1.2571	1.0553
Quercus	1.0857, 1.1282, 1.1481, 1.4541	1.2040
Carpinus	1.6331	1.6331

(After Hoare 2020, Thery-Parisot et al. 2014).

Mean = 0.9894.

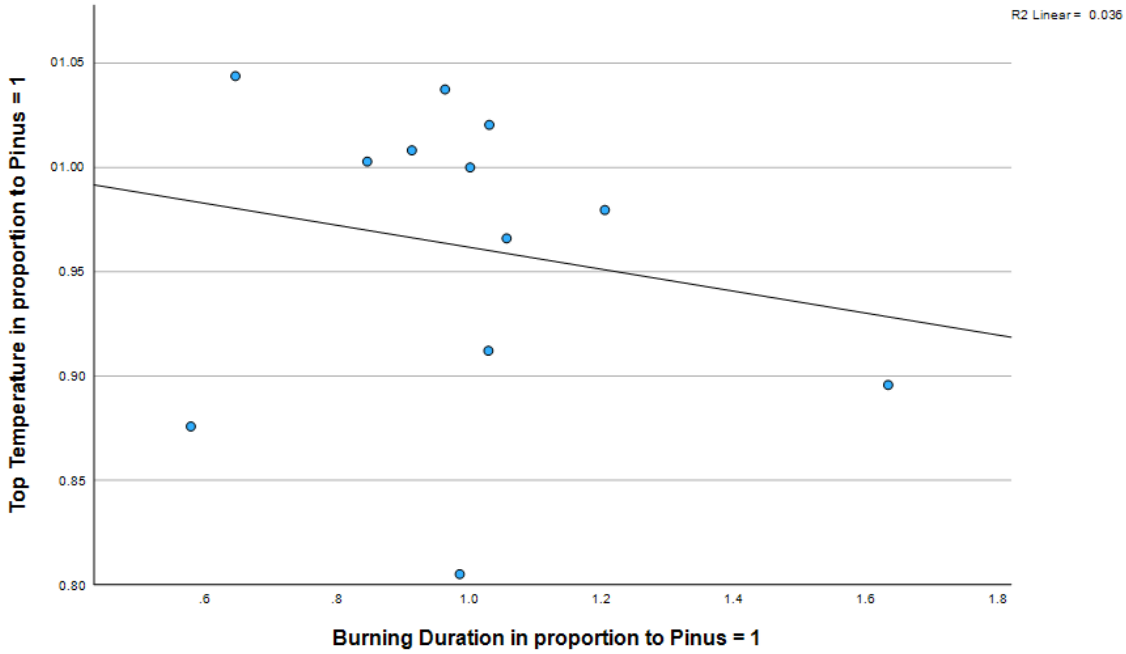
When assessing burning duration, the above studies looked at real experimental fires. In these, whilst different genera differ due to varying densities and chemical compositions, differences also occur from varying branch sizes, and compactness/diffuseness of burning piles. The above studies can be contrasted to charring rate. Under more rigorous laboratory conditions at set temperatures, rates of combustion depend on wood density/chemical composition alone. Although charring rate and burning duration theoretically correlates, this correlation is weak (Graph 9.8, below), because of the abovementioned variabilities. In general, burning duration should be preferred to charring rate, as coming from more realistic studies; however many fewer studies burn in realistic settings, and those which do vary much more through external variables such as wind and ambient temperature, although Hoare (2020) accounts for the latter. Due to these variations, there is no correlation between duration of combustion and wood-to-charcoal rates (Appendix Seven: Graph A24), despite in theory slower-burning fuels creating more charcoal, if burnt at lower temperatures. Likewise, burning duration only somewhat correlates with density (Appendix Seven: Graph A23), as expected, as denser fuels burn slower, and any variations stem from variable branch morphology.

There is much more variability in burning duration than the other properties, and it is a highly sought-after aspect of fuelwoods. Carrying heavy, bulky fuels would have been an important daily job, but would have left foragers vulnerable to attack or predation en-route if they not also carrying other defensive tools. Slower-burning fuels, even if emitting less heat or light overall or at a single moment, require less overall fuel to be gathered for an evening's fire. It would reduce frequencies of waking to refuel fires left burning overnight. Hot-burning *Picea*, a also burns quickly, as expected, as does *Betula*, and *Alnus*, a softwood. However *Populus*, another softwood, burns at almost the same rate as pine. Again, *Larix* has longer burning times but lower temperatures, further highlighting the *Larix-Picea* dichotomy as regarding the type of fuel they are. *Quercus*, a common but lower-presence fuel, burns notably slowly, further suggesting that it may have been added to burn overnight or during absences from the fire.



Graph 9.8: the imperfect positive correlation between charring rate and burning duration (R2 = 0.076). Burning duration partially depends on charring rate, but also on many other variables including wind speed, fuel loading positions etc.

Burning duration may negatively correlate with maximum temperature, as fuels releasing heat slower would last longer but attain lower peak temperatures. Graph 9.9 does show a negative correlation, however with the notable exceptions of *Alnus* and *Populus*. Both these fuels are rare in Neanderthal fires however.



Graph 9.9: a negative correlation between top temperature and duration of combustion for various fuels (R2 = 0.036). This was expected, given that if fuelwoods have a standard amount of energy to release, if it is released at once, it will both give off a sudden higher temperature, and also last a shorter time.

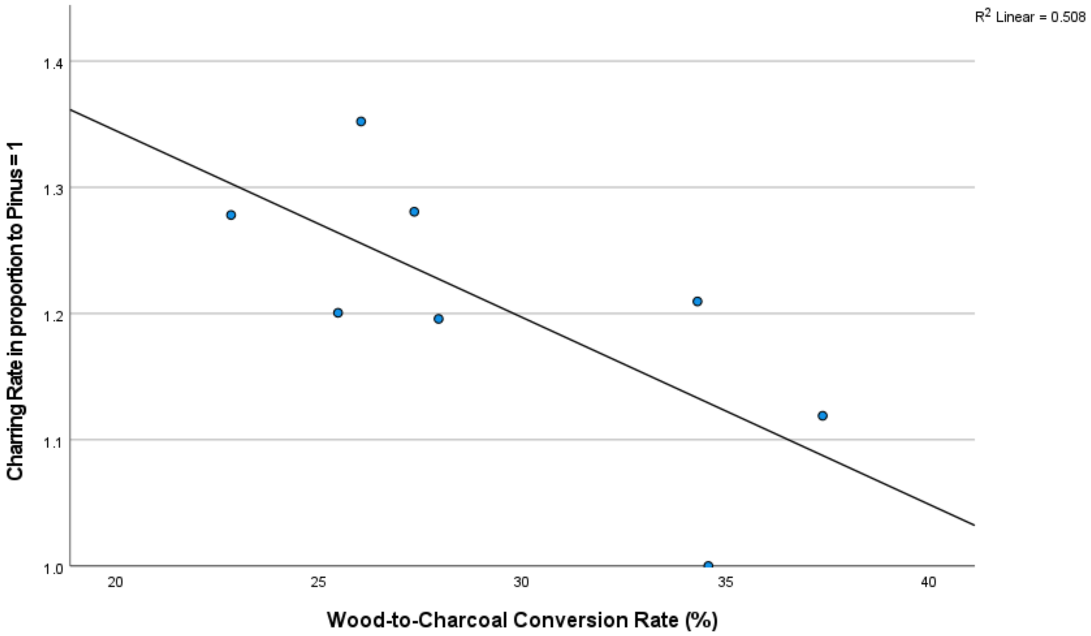
III.III: Charring Rate.

Table 9.7: 8 genera ranked in proportion to pine for the charring rate (amount of time taken to char under a set temperature in mm^2/min); a higher value indicates a longer time taken to char.

Genus	**Proportions compared to *Pinus* = 1**	**Mean Proportion compared to *Pinus* = 1**
Pinus	N/A	1
Castanea	1.119	1.119
Acer	0.926, 1, 1.1645, 1.1727, 1.2354	1.1958
Betula	1.179, 1.2222	1.2006
Picea	1, 1.1361, 1.2793, 1.3112, 1.3212	1.2096
Fagus	1.2781	1.2781
Fraxinus	1.2807	1.2807
Quercus	1.1768, 1.3334, 1.343, 1.5556	1.3522

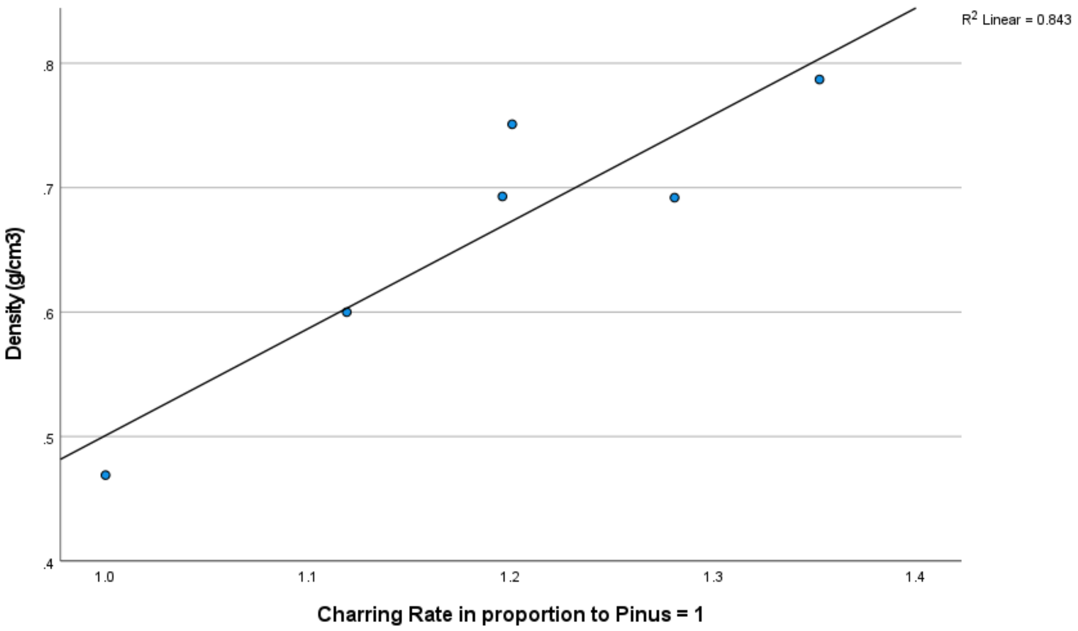
(After Bryan and Doman 1940, Hugi et al. 2007, McNaughton 1942, White 1988, White and Nordheim 1992). Mean = 1.2045.

Charring rate itself is more relevant to charcoal production than to fuel value. Wood rarely burns as single branches, but interacts with other fuel pieces and embers in ways determined by fuel genera morphologies. With charcoal production, internal combustion of single wood chunks is more important than interaction with other fuel pieces. Slower-burning woods have more time for semi-liquid char deposits to build up on their surfaces, sealing off the insides and limiting further burning and oxygen intake, and increasing wood-to-charcoal conversion rates. A good negative correlation is noted (Graph 9.10), with R^2 linear = 0.508, suggesting that charring rate accurately predicts wood-to-charcoal conversion rates.



Graph 9.10: the negative correlation between charring rate and wood-to-charcoal conversion rate (R2 = 0.508). This correlation is a little unclear, given that whilst charring rates correlate well with density, wood-to-charcoal conversion rates do not. Nonetheless. This suggests that charring rates could be used as a useful proxy for wood-to-charcoal conversion rates, or vice-versa.

As expected, Charring Rate positively correlates with wood density (Graph 9.11, R^2 = 0.843). Since this was determined under laboratory conditions, density and chemical compositions will be the only variables involved. This indicates that density is a good proxy for charring rate; and to some extent, for burning rate.



Graph 9.11: the almost perfect correlation between density and charring rate (R2 = 0.843). Given that charring rate is measured under perfect environmental conditions, without external factors, density would be expected to be the most important indicator of charring rate.

III.IV: Light Emitted.

Table 9.8: 8 genera ranked in comparison to pine for the amount of light given off when burnt (higher values indicates more light emitted from a fire of that genus).

Genus	**Maximum Light Emitted (Lux)**	**Proportion compared to *Pinus* = 1**
Quercus	8.7	0.435
Alnus	19.3	0.965
Pinus	20	1.00
Larix	23	1.15
Picea-Larix	N/A	1.275
Picea	28	1.4
Fagus	34	1.7
Fraxinus	39	1.95
Betula	51	2.55

(After Hoare 2020, 0.5m fire, 7kg fuel).

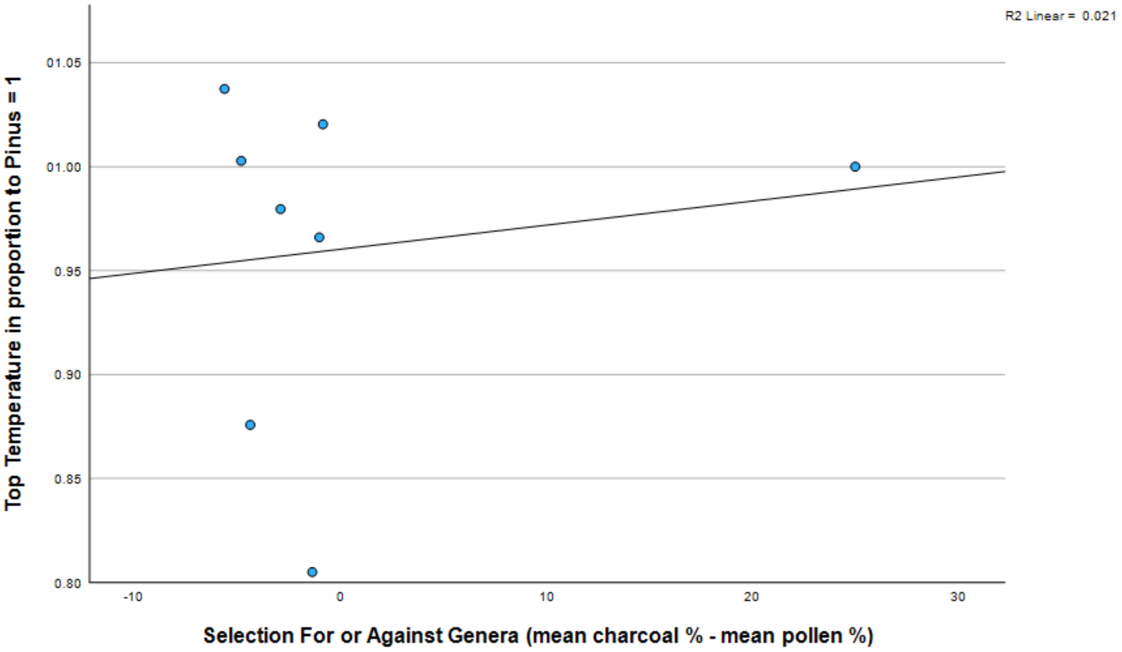
Mean = 1.3938.

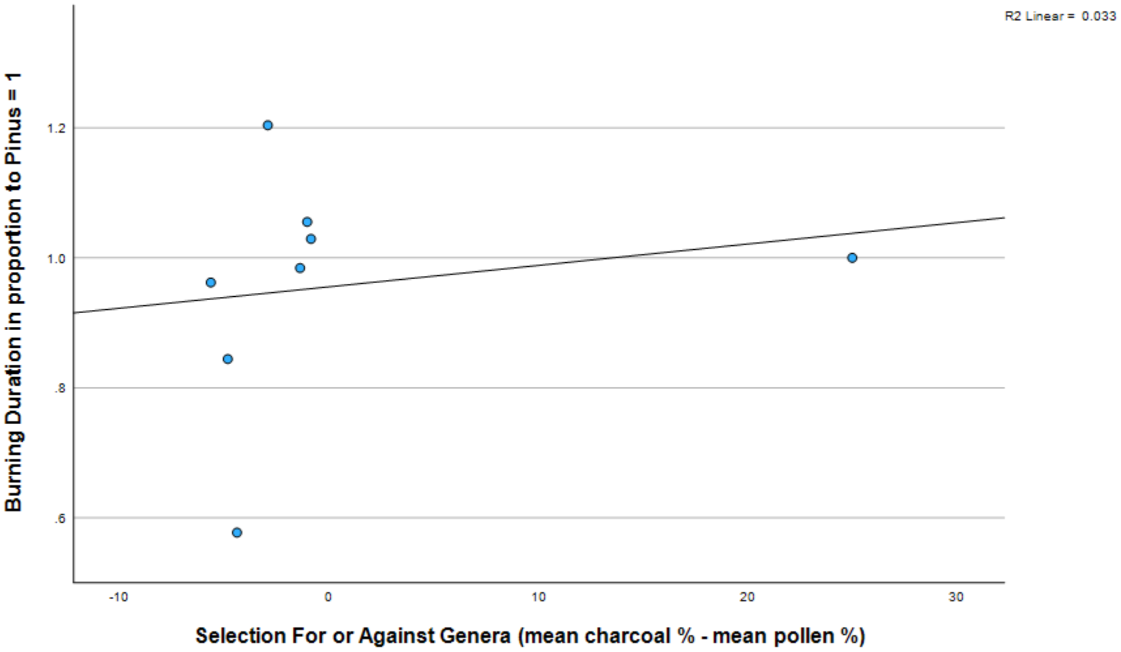
Tables 9.9-9.10: Comparing the propensity of different genera to create: sparks, smoke, and embers; both after Hoare 2020.

Sparks and Smoke	**Genera**
Sparks/high smoke	*Alnus, Betula, Picea*
No sparks/low smoke	*Fagus, Fraxinus, Larix, Pinus, Quercus*

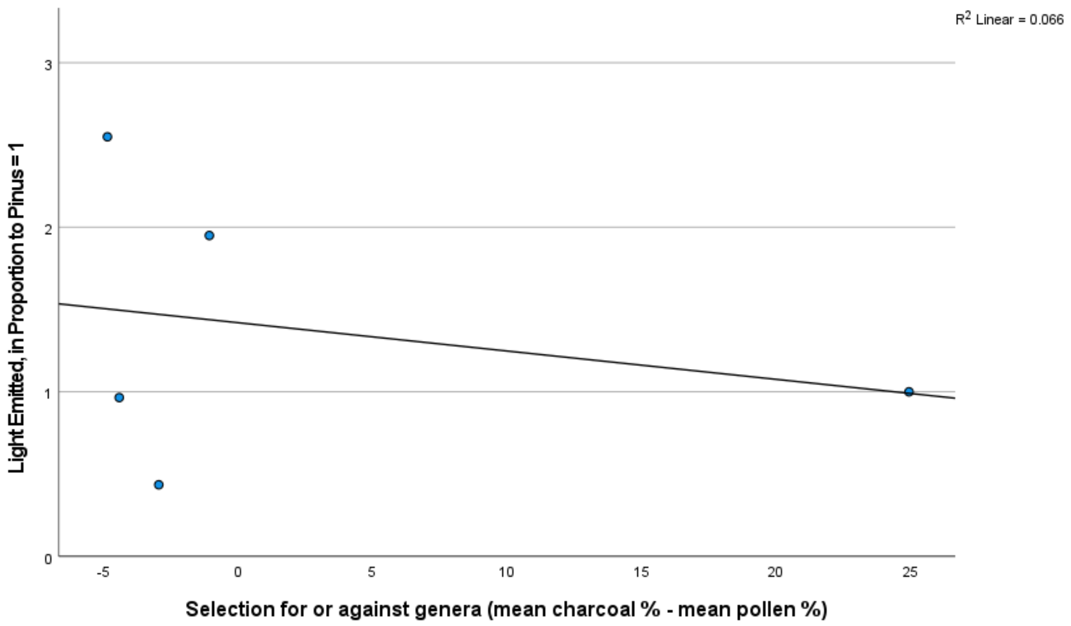
Embers	**Genera**
Yes	*Alnus, Betula, Fagus, Fraxinus, Larix, Picea, Pinus, Quercus*
No	-

In Iberian landscapes, there is no correlation between fuel *availability* and the fuel's top burning temperature, rate of burning or light output. Unlike Neanderthals potentially choosing less-dense woods at random because of local abundance, Iberian Neanderthals would not have been automatically biased towards other fuelwood traits. When we look at their selection, Neanderthals do not select towards top temperatures or burning duration (Graphs 9.12-9.13). There is minimal selection against fuels with high light outputs (Graph 9.14, $R^2 = 0.066$); however this might be an artefact of having so few fuels with both selection and light output data available. Alternatively, selection against light output, if energy instead releases as heat (over time, instead of attaining higher top temperatures), suggests selection towards fuels with higher heat output at the expense of light.





Graphs 9.12 and 9.13: Graphs detailing the lack of selection for or against fuels with high burning temperatures (R2 = 0.021) and long burning durations (R2 = 0.033), respectively.



Graph 9.14: the apparent selection against fuel genera with high light outputs when burnt (R2 = 0.066). This selection may however result from the few data points available, or instead represent selection towards genera with greater heat outputs.

Smoke is often unwanted, unless explicitly being used for meat-smoking or smoke-signalling (for modern ethnographic examples see Brandisauskas 2010, Henry and Thery-Parisot 2014, Henry et al. 2018). However for general heating and lighting uses, smokeless fuels would have been highly advantageous. The favoured fuel, pine, can create either little or some smoke, depending on conditions (particularly taking cave morphology into account – Fuente-Fernandez 2022, Kedar and Barkai 2019, Kedar et al. 2020); however those genera Hoare notes as creating abundant smoke, *Alnus* and *Betula*, are both selected against (-4.64%). These genera also create sparks, potentially injuring fire users. The relative abundance of birch fuel may come from its value as a fire-starter. Looking at incidences of different fuel genera in the overall Neanderthal record, confirmed sparking/smoking genera are only found in 23 Middle Palaeolithic layers (4.94% of all Neanderthal fires), with *Alnus* not burnt anywhere. Confirmed non-sparking/smokeless genera are however found in 121 Middle Palaeolithic layers (57.33% of all Neanderthal fires).

Neanderthals avoided the worst genera for each trait; the worst three genera for temperature only form 1.99% of the charcoal (in 23 layers), as opposed to 7.65% (in 22 layers) for the best three genera. Welch’s two-sample T-test suggests that these two values were statistically distinct (p = 0.01876). Likewise, the three quickest-burning genera form 6.86% of the assemblage (in 14 layers), and the three longest-burning ones form 13.17% (in 71 layers) – this is statistically-insignificant (p = 0.05418). This trend wholly reverses for light, whereby the three genera producing least light dominate the assemblage (52.63%, in 95 layers), and those three producing most light only form 2.78% (in 35 layers) – again, a statistically-significant difference (p = 0.01836). Light output seems to have been of minimal concern for Neanderthals, and genera emitting little light, *Quercus* and *Pinus*, were still chosen for other favoured properties.

This suggests that Neanderthals selected for obvious, visual traits, such as lack of smoke or sparks, and less understood heat output or burning duration. However, given that they may also have selected for less-dense woods, foraging concerns may have been more important than how the fires themselves functioned. Although Neanderthals were not apparently universally selecting for it, burning duration would have been important not only for the hearth but also for foraging practices. With standardised wood loads, fires made of slow-burning fuelwoods would last longer; for desired fire durations, smaller loads of slow-burning fuels would have been needed than fast-burning ones. Thus slow-burning fuels would have been equally important for foraging as for optimisation. Neanderthals' selection of less-dense woods might indirectly cause selections towards faster-burning ones, thus requiring higher fuel loads. However, this practice varied group-by-group, and determining average Neanderthal fire traits, differing in each site, explores these variations in foraging practice.

The results below represent traits of average Neanderthal fires in each site layer, in comparison to standard pine fires. Given that Neanderthals burned 42 different genera, and combustion information only exists for 12 (or 8 for light emissions), I can only analyse some sites. I include sites with some untested genera, up to a maximum of 25% of the total assemblage, using the average values for each criterion for the untested genera.

Table 9.11: Site-by-site comparisons of temperature, burning duration and light emitted from the fires in that site, ranked against each other. No site in this table uses an average value (for untested genera) for more than 25% of the charcoal assemblage. Averaging values is suboptimal, but to exclude untested genera would not only mean that sample sizes would be too small, but that certain types of wood (e.g. evergreens) would be artificially underrepresented as they are tested less frequently.

Site and Level	**Top Temperature**	**Duration of Combustion**	**Light Emitted**	**Percentage of Charcoal Assemblage where an Average is used**
El Esquilleu Level XIV-XIX	0.999	0.9965	1.0417	2.45
El Esquilleu Level XX-XXX	1.0000	0.9950	1.0496	0
Cova de Coll Verdaguer Unit I	0.9935	1.0002	1.0399	12.15
Cova de Coll Verdaguer Unit II	0.9977	0.9994	1.0211	5.37
Cueva del Camino Level V	0.9991	0.9871	1.1452	0.47
Gorham's Cave Level IV	0.9993	0.9979	1.0257	6.53
Abric Romani Zone V	0.9988	1.0011	1.0096	3.3
Abric Romani Zone IV	1.0000	1.0000	1.0003	0.07
Abric Romani Zone III	0.9999	1.0000	1.0005	0.13
Abri du Maras Layer 4	0.9954	0.9989	1.0421	10.69
Abrigo de la Quebrada Level VIII	0.9979	1.0004	1.0136	4.2
Aguilon P5	0.9992	0.9998	1.0071	1.8
Bojnice III Layer IX	0.9825	0.9301	1.1345	4.65
Bolomor Cave Levels XI & XIII	0.9969	0.9279	1.0284	7.21
Cova Gran S1B-S1F	0.9985	1.0008	1.0034	1.57
Cova 120 Level V	0.9968	0.9992	1.0297	7.54

Site and Level	**Top Temperature**	**Duration of Combustion**	**Light Emitted**	**Percentage of Charcoal Assemblage where an Average is used**
Cova 120 Level VI	0.9932	1.0071	1.1425	10.83
Cueva Anton Complex AS3	0.9936	1.0157	1.0039	13.14
Cueva Anton Complex AS5	0.9878	1.0366	0.9562	15.89
Cueva del Conde Level N10	0.9951	0.9841	1.2419	10.37
De Nadale Cave Unit 7	0.9879	0.8882	1.3713	0.99
El Salt Unit VIII	0.9972	1.0033	1.0121	5.74
El Salt Unit IX	0.9848	1.0031	1.0701	21.69
El Salt Unit Xa	0.9905	1.0078	1.0432	17.53
El Salt Unit Xb AFA 1	0.9931	1.003	1.0441	14.4
El Salt Unit Xb AFA 2	0.9937	1.0034	1.0358	12.44
Grotta di Fumane Unit A9	0.9506	0.9206	1.2243	0
Les Canalettes Level 3	0.9955	1.005	1.0409	9.48
Les Canalettes Level 4	0.9985	0.9994	1.0291	4.75
Llonin Cave Levels VIII CP, VI Gal	0.9992	0.9405	1.6029	4.28
Nesher Ramla Levels I-VIi1	0.9747	1.157	0.6451	21.91
Pod Hradem Cave Level 11	0.9822	0.8776	1.2082	0.74
Pod Hradem Cave Level 10	0.9734	0.8475	1.2817	0.84
Pod Hradem Cave Level 9	0.9784	0.8733	1.234	2.89
Scladina Cave Unit 2B	1.0159	0.8545	1.2031	3.86
Scladina Cave Unit 4A	0.9711	1.1064	0.813	16.8
Range	0.9506-1.0159	0.8475-1.157	0.6451-1.6029	

This set excludes fires consisting of mostly other, unstudied, genera and will thus tend to cluster around pines' values, which is the primary fuel in 29 of 36 site levels studied here; the exception being *Quercus* in Nesher Ramla Levels I-VIi1 and Scladina Unit 4A, *Larix* in Grotta di Fumane Unit A9, and *Picea/Larix* in De Nadale Unit 7, and Pod Hradem Levels 9-11. The fact that *Picea* and *Larix* are averaged for their combined values further drives values towards 1. *Picea/Larix* are seldomly differentiated as their similarities in both charcoal and pollen means that accurate diagnoses are often impossible, and cannot be excluded from this analysis as too few sites would remain for accurate insights. Averaging traits of these two genera is more accurate than using averages of all genera's traits, which would be the alternative if *Picea/Larix* were rejected (and their proportions added to the percentage of charcoal assemblages where averages are used). Furthermore, *Picea* and *Larix* often grow nearby each other, and could have been gathered in similar proportions, so '*Picea/Larix'* samples may contain similar proportions of each. However, within these samples, top temperatures vary minimally from site to site, regardless of fuel composition. Any differences depend much more on fire size, hearth construction and rates of fuel input.

Burning duration, more directly tied to fuel quantity, varies more. Many cluster around 1 (pure pine fires); fires with 95%+ *Pinus* fuel include El Esquilleu Levels XIV-XIX and XX-XXX, Abric Romani Zones III-V, Abrigo de la Quebrada Level VIII, Aguilon P5 and Cova Gran S1B-S1F. Abric Romani Level N has a mean diameter of fires of 0.58m (Vallverdu et al. 2010, p.140), mostly corresponding to Hoare's 0.5m diameter experimental fires; however two are over 1m wide (hearth nos. 8 and 16), corresponding to Hoare's 1m fires.

- If these 1m fires functioned similarly to Hoare's 1m fires, the Abric Romani fires peaked at 751-880°C for 45-60 mins, flaming for 110-150 mins.

It is unknown how many Neanderthals would have been around the larger fires; but just one individual could have fuelled the smaller fires. If Neanderthals refuelled their fires as Hoare did (near the end of flaming periods):

- 0.5m diameter (personal) fires would have consumed 7kg pine fuel per 110 minutes burning. Rate of Fuel Consumption (RFC) = 0.0636kg/min.
- 1m diameter (group) fires would have consumed 35kg pine fuel per 125-150 minutes burning. Rate of Fuel Consumption (RFC) = 0.2333 to 0.28kg/min.

As Hoare (2020) and Thery-Parisot et al. (2014) added standard amounts of fuel at the start of the experiment and observed the burning duration, I can determine Rates of Fuel Consumption for the genera in their experiments, for c.0.5m diameter fires (Table 9.12 beneath).

Table 9.12: The mean rate of Fuel Consumption for each tested genus, as determined from Hoare (2020) and Thery-Parisot et al. (2014). This represents an average for each genus, and is only appropriate in a fire composed exclusively of that genus.

Genus	**Mean Rate of Fuel Consumption (kg/min)**
Alnus	0.1102
Picea	0.0987
Picea/Larix	0.0761
Betula	0.0753
Fagus	0.0698
Corylus	0.0661
Populus	0.0646
Pinus	0.0636
Larix	0.0619
Olea	0.0618
Fraxinus	0.0603
Quercus	0.0528
Carpinus	0.0389

Neanderthal sleep patterns are unknown; however if compared to the Hazda, Ju'hoansi and Tsimane (Yetish et al. 2015), they would have slept c.5.7-7.1 hours, with 1h more in winter than summer, initiating sleep 2.5-4.4 (mean of 3.3) hours post-sunset. Neanderthal genes, particularly the RS1159814 allele, regulate modern human circadian rhythms in northern climates (Putilov et al. 2018), which of course differ from Yetish's African study. An alternative study suggests that the Sima de los Huesos hominins fully hibernated in winter (Bartsiokas and Arsuaga 2020). However these early Neanderthals may have had far less fire, and fire use itself may have changed winter sleeping and behaviour patterns. Neanderthals would also have had to wake every two hours to refuel their fire. Modern hunter-gatherers use 'early' and 'late' sleeps, with waking periods in between, with potential for refuelling. Of course, group settings could be different. Asynchronous sleep patterns caused by chronotype variations are important in hunter-gatherers for keeping watch and group security (Samson et al. 2017). Awake individuals could altruistically fuel everyone's individual fires, in return having their own fire fuelled later when they sleep.

If all Neanderthals required fire to see in the dark, and maintained fires all night for security, how much fuel would they have needed?

A = awake time after dark. $2.5 \leq A \leq 4.4$h ($150 \leq A \leq 265$mins).

S = sleep time. $5.7 \leq S \leq 7.1$h ($345 \leq S \leq 425$mins).

T = total fire time. T = A + S

Durations of waking and sleeping anticorrelate (if they went to bed later they would sleep for less time), therefore:

T = $(A_{min}+S_{max}) \leq T \leq (A_{max}+S_{min})$. $9.6 \leq T \leq 10.1$h ($575 \leq T \leq 610$mins).

Pine Fuel Consumption (PFC) = T(mins) x Rate of Fuel Consumption (kg/min).

Therefore, small pine hearths: $575 \times 0.0636 \leq PFC \leq 610 \times 0.0636$ = 36.57 to 38.80kg of pine.

Large pine hearths: $575 \times 0.23333 \leq PFC \leq 610 \times 0.28$ = 134.16 to 170.8kg of pine.

If a small pine hearth corresponded to one Neanderthal's efforts, they would have to gather c.36.6-38.8kg of fuel per day. An Abric Romani pine-fuelled fire would have used this much overnight. However, this varies between sites as different fuels are burned (assuming identical hearth sizes and conditions), causing different Rates of Fuel Consumption. Each site is not composed of only one fuelwood genus either. To calculate fuel consumption for a site, the following equation is needed.

Site Fuel Consumption (SFC) = ((RFC(A) x A.) + (RFC(B) x B.) + (RFC(C) x C.)……) x T

A, B, C…. = genera A, B, C….

RFC(A) = rate of fuel consumption for genera A (kg/min)

A. = percentage of genus A in the charcoal record.

T = time the fire is alight, awake time (A) + sleep time (S) (mins).

I am unable to calculate SCF for all sites and layers however, as not all genera present were tested by Hoare or Thery-Parisot and have a RFC available. The two extremes we find are Pod Hradem Level 10, and Nesher Ramla. Individuals in Pod Hradem Level 10, with otherwise identical but faster-burning fires, would consume 43.2kg fuel, and ones in Nesher Ramla would use 31.6kg. If Neanderthals could carry half their body weight (see Chapter Five, p.137), males carried c.36-42kg per load and females 32-33kg (Biran et al. 2004, Froehle and Churchill 2009).

Light emitted was by far the most variable output, and would also have been especially important for cave sites after dark, to enable tasks to be undertaken accurately, and to signal presence to other groups and predators. Light output is more difficult to gauge than temperature or duration, as it varies depending on distance from the fire. Outputs to the landscape cannot be determined; we can only look at what Neanderthals around the fire would have seen. Most of the Abric Romani Level N hearths (Vallverdu et al. 2010) were c.1m from the wall, suggesting the Neanderthals were within that distance; a 0.5m fire, with a viewer within 1m, creates 12 lux throughout most of its burning, although peaking at 20 lux for 45 mins (Hoare 2020). This is less light than larger fires; 17 lux normally, peaking at 20.3-29 lux for 40-90 mins. Tasks can require from 27 lux (Gronli et al. 2016). However, Neanderthals may have had more of their brain dedicated to sight, and thus better night eyesight than AMH (Pearce et al. 2013). We do not know thresholds for different Neanderthal tasks; however given the many pine-dominated fires, and the success of these groups, these illumination levels must have been sufficient. However, lower light levels with high radiative heat outputs may have helped sleep, as high light levels cause insomnia (Gronli et al. 2016). Light output for fires in various sites and layers are calculated in a similar manner to burning duration and quantity of fuel needed.

Light Output = ((L(A) x A.) + (L(B) x B.) + (L(C) x C.)……)

L(A) = lux output for genus A.

A. = percentage of genus A in the charcoal record.

As with fuel usage, only certain sites and levels could be tested as Hoare and Thery-Parisot only tested certain genera. Nesher Ramla and Llonin were the two extremes of light output for their fires (7.7 and 19.2 lux respectively). Lower-lux fuelwoods may have been favoured for sleeping hearths, and higher lux ones for activity hearths.

However, what of Neanderthal fires dominated by other fuels, for which we have no information? In particular, *Juniperus* dominates 7 levels, *Olea* dominates 4, *Carpinus* 2, and *Amygdalus, Acer* and *Sorbus* 1 each. However, juniper was not tested by Hoare (2020) from which I base my information. If juniper burns like other conifers (pine, larch or spruce), then its values should cluster close to 1 with its similar densities and resin contents, and similarly-sized branches, suggesting similar ignition behaviours. Had I undertaken all these experiments myself, I would of course have included *Juniperus*, however Hoare (2020), whose experiments I base these values off, omitted it from their studies.

IV: Methodology.

Density correlates with Charring Rate (Graph 9.11, p.265), and Charring Rate with Burning Duration (Graph 9.8, p.262). Both have positive correlations. I could therefore use density as a proxy for burning duration (Appendix Seven, Graph A23, although this correlation is weak), and thus for Rate of Fuel Consumption. I took density values for different genera from established literature, already outlined in Table 7.11, p.187.

- Charring Rates, Burning Durations and Density values were all already analysed using values ratioed to the corresponding values of *Pinus* = 1 (a genus with a value of 0.5 charred twice as slowly, burn half as fast or was half as dense as pine, depending on the metric).

Therefore I could have mapped Density directly onto Burning Duration, and thus onto Rate of Fuel Consumption. This would be important for genera excluded from Hoare's study and for which RFCs could not be calculated. However, *Pinus* is itself an outlier to this line, having much lower densities than expected for its burning duration (possibly due to its slow-burning resin content). *Pinus* specifically was a poor genus to which to ratio the values for other genera.

I instead calculated values in proportion to another common genus instead, *Quercus*, which was along the regression line of the density-burning duration correlation graph (Appendix Seven, Graph A23). *Quercus* was appropriate as it was the second most common fuel (see Table 8.35, p.237) and was included in the most experiments on this subject. Therefore I used *Quercus* = 1.204 for the standard around which density was measured, ignoring *Pinus* in this instance.

This gave me the burning duration, as density values around *Quercus'* value. I subsequently calculated Rate of Fuel Consumption (RFC) for each genus. As *Quercus* was used as a density number, I calculate RFCs from *Quercu*s' value of 0.0528kg/min, calculated on p.273. If Burning Duration doubles, RFC halves under standard fuel inputs. For 3 genera, A, B (*Pinus*) and C, A has half the density of *Quercus* (0.5:1 ratio) and C has double its density (2:1 ratio):

RFC(A) = RFC(*Quercus*) ÷ (density[A] proportional to *Quercus*])

RFC(A) = 0.0528kg/min ÷ 0.5 = 0.1056kg/min

RFC(B) = 0.0528kg/min ÷ 1 =0.0528kg/min

RFC(C) = 0.0528kg/min ÷ 2 = 0.0264kg/min

The results are presented in Table 9.13. Given that RFCs for additional genera are known, Site Fuel Consumptions (SFCs) can be calculated, using the following formula:

Site Fuel Consumption (SFC) = ((RFC(A) x A.) + (RFC(B) x B.) + (RFC(C) x C.)……) x T

A, B, C…. = genera A, B, C….

RFC(A) = rate of fuel consumption for genera A (kg/min)

A. = percentage of genus A in the charcoal record.

T = time the fire is alight, awake time (A) + sleep time (S) (mins).

The results are presented in Table 9.14.

V: Results.

Table 9.13: Different densities of studied genera, in this instance ranked from lowest to highest densities. Density values are taken from Table 7.11, p.187. As pine is unusually non-dense for its rate of fuel consumption compared to the average, it was not appropriate to base my calculations around it; I compared each to Quercus instead, multiplying each value by 1.204, the difference between Pinus and Quercus, to approximate in proportion to Pinus = 1.

Genus	**Density Values (means in g/cm^3)**	**Proportion compared to *Quercus* = 1.204 (thus *Pinus* = 1)**	**Mean Rate of Fuel Consumption (kg/min), inferred from Density**
Castanea	0.6	0.92	0.0693
Acer	0.693	1.06	0.0600
Arbutus	0.713	1.09	0.0598
Carpinus	0.711	1.09	0.0585
Olea	0.715	1.09	0.0581
Prunus	0.74	1.13	0.0562
Erica	0.76	1.16	0.0547
Ulmus	0.771	1.18	0.0539
Quercus	0.787	1.20	0.0528
Pistacia	0.788	1.21	0.0514
Juniperus	0.81	1.23	0.0598
Sorbus	0.864	1.32	0.0481
Phillyrea	0.875	1.34	0.0475
Amygdalus	0.882	1.35	0.0471
Rhamnus	0.955	1.46	0.0435
Buxus	1.07	1.64	0.0389

Table 9.14: sites with the site fuel consumption estimated based on the genera in the fires, where a large proportion of the burning duration is estimated from the density of the woods themselves. For simplicity, a rough mean of T (575 to 610) has been taken, and T = 590. See Table 9.13 and p.277 for the methodology of this calculation.

Site and Level	Site Fuel Consumption (kg) for a single 0.5m fire for 9.6-10.1 hours, taking all genera into account.	Percentage of Charcoal Assemblage where an Approximation of Burning Duration by Density is used
El Esquilleu Level IX-XIII	32.91	50.92
Abric del Pastor Unit IVc	37.58	81.69
Abric del Pastor Unit IVd	38.77	88.56
Cova 120 Level IV	36.65	8.31
Cueva Anton Complex AS2	38.75	44.71
Cueva del Conde Level N20A	35.20	30.53
El Salt Unit Xb AFA 3	36.54	26.29
Kaldar Cave Layers 4-5	34.94	28.45
Klissoura Cave Layer XXI	33.72	21.75
Klissoura Cave Layers XXg-XXe	32.75	38.96
Klissoura Cave Layers XXd-c	33.56	37.04
Klissoura Cave Layer XXb-a	32.79	28.76
Klissoura Cave Layer XIX	34.99	12.47
Klissoura Cave Layer XVIII	33.80	22.14
Klissoura Cave Layer XVII	32.19	31.42
Klissoura Cave Layer XVI	30.18	67.27
Klissoura Cave Layer XV	30.85	91.04
Klissoura Cave Layer XIV	30.78	93.63
Klissoura Cave Layer XIII	33.01	90.57
Klissoura Cave Layer XII	35.04	78.35
Klissoura Cave Layer XI	35.54	81.73
Klissoura Cave Layers X-IX	31.18	46.5
Klissoura Cave Layers VIII-VII	33.13	69.78
La Vina Cave Levels XIIIbas, XIV, XV, I.A, I.B	39.18	23.37
Les Canalettes Level 2	31.82	28.2
Riparo Bombrini Stratum IV	32.51	85.48
Teixoneres Cave Levels II, IIb and III	30.93	28.65
Theopetra Cave Layer II3	30.08	65.28
Theopetra Cave Layer II4a	32.96	74.75
Theopetra Cave Layer II4b	33.03	90.15
Theopetra Cave Layer II5	28.37	19.11
Theopetra Cave Layer II6	27.60	11.83
Theopetra Cave Layer II7	31.17	42.34
Theopetra Cave Layer II8	32.83	31.6
Theopetra Cave Layer II10	39.73	100
Theopetra Cave Layer II11	35.40	80.65
Range	**27.60-39.73kg**	**8.31-100%**

Average fire durations here are higher than if calculated from experimental fires, further suggesting that density is an imperfect proxy for burning duration, and tends to estimate longer burning durations than real-life fire experiments. Based on this, the minimum fuel that Neanderthals (at Theopetra Layer II6) could have used overnight, was 26.8kg. This is much less than the 43.2kg for the Pod Hradem Neanderthals (calculated on p.275), indicating how changes in fuelwood genera greatly reduce individual daily workloads. It must be noted however that the Pod Hradem Level 10 *Picea/Larix* fire would have emitted much more light than the Theopetra II6 *Quercus* fire.

Fuelwoods can be divided into various categories, depending on hearth function. Hoare and Thery-Parisot studied northern European woods, and Mediterranean genera such as *Juniperus* and *Buxus* remain unstudied. However many colder-climate fuelwoods would have been suitable for high temperatures, although *Alnus, Carpinus* and *Populus* would have been the worst for this. *Alnus* would likewise have burnt quickly, alongside *Picea, Larix* and *Betula*, and better, slower-burning fuels include *Fraxinus, Quercus* and *Carpinus*. Finally, *Quercus, Alnus* and *Pinus* emit little light, whilst *Fagus, Fraxinus* and *Betula* are optimized for this. Of fuelwoods studied here, all except *Alnus* and *Fagus* were common fuels. Given that alder emits little heat, and burns quickly whilst emitting little light, it is undoubtedly the worst fuel here. It is also not burned in any Neanderthal site. It was available environmentally (in varying quantities) at many sites (where pollen is available to study), including El Esquilleu, Cova de Coll Verdaguer, Cueva del Camino (forming almost 20% of the pollen), Bolomor Cave and Riparo Bombrini. Its complete absence as a fuel, despite its availability, suggests that Neanderthals recognized its unfavourable burning properties for their purposes and avoided it. Another variable is latitude which appears to affect fuel choice relating to temperature output. *Carpinus* (hornbeam) burns at low temperature but burns slowly (its light output is unmeasured); it is also found exclusively in more southerly sites including Klissoura and Theopetra. This suggests that hot-burning fuels were more valued in northern latitudes, but more southerly Neanderthals valued slow-burning fuels more.

VI: Conclusion.

This chapter has examined two aspects of fuel choice; wood qualities, and their subsequent effects on burning events. The first analysis suggested that Neanderthals may only have selected easy-to-break woods, which would only have been motivated by foraging principles. *Pinus,* a strongly-preferred fuel, has moderate calorific values but notably low densities, and thus would have been very portable. Natural Iberian Middle Palaeolithic landscapes, as determined by pollen, tended slightly towards less-dense trees which may explain this selection. Neanderthals appeared to select for woods with lower calorific values, an unexpected trait, which however may be an artefact of lower-calorie woods creating more charcoal, or of them selecting lower-density woods. However, when examining correlations between wood qualities and actual burning qualities, charring rate (the rate at which wood burns by volume in experimental conditions) positively correlates with density, and charring rate also correlates well with wood-to-charcoal conversion rates. Similarly, fuels with shorter burning durations also achieve higher top temperatures, as expected, which suggests that in any fuel, trade-offs are made at the expense of one of these traits. Where selection could be observed in Iberia, Neanderthals did not select for observed burning traits; instead, they may have selected for the more obvious traits of no sparks or smoke. They selected woods with other favoured burning traits, at the expense of high light outputs, as low light-output fuels were more common. Exceptional Neanderthal night vision (Pearce et al. 2013) may have caused this selection, whereas poorer-sighted AMH may have valued light more than heat. Neanderthals also notably selected against *Alnus*, a low-ranking fuel, despite it being widely available in large quantities (20% of the pollen in Cueva del Camino).

All these theoretical burning traits have been mapped onto actual Neanderthal fires layer-by-layer, determining that whilst top temperatures vary minimally between sites and layers, burning duration and especially light output varied much more. By mapping Hoare’s studies onto the Abric Romani fires, I have determined that some Neanderthal groups used 1.6x the fuel that others would, simply from how slowly different fuelwoods burn. This may have made the difference between making one or two daily fuel-foraging trips, and may have determined whether juveniles, elderly or injured individuals could have been effective wood-gatherers. Given apparent Neanderthal interest in minimizing foraging through fuel properties, the next chapter examines the sites’ surrounding environments, and individual fuel regimes, which woods were burnt and which avoided, and why this was the case.

Chapter Ten: Simulated Foraging Experiments.

The previous chapter has examined motivations behind Neanderthal fuel choice, concluding that whilst certain fuel genera (e.g. *Alnus, Fagus*) were inferior fuels, most other fuels had similar burning traits, and Neanderthals instead focused on streamlining and optimizing fuelwood foraging processes. This is simultaneously distinct from and similar to the Principle of Least Effort. Whilst Neanderthals minimized foraging effort, they did not take nearby fuelwoods, but instead chose those which were easiest to break and transport, and those burning slowest. To understand these foraging choices, this chapter replicates Neanderthal foraging in five modern environments most closely resembling landscapes around the study sites, to replicate Neanderthal foraging experiences. Subsequent analysis of landscapes around the study sites shows the genera discrepancy in each area, with forested and open landscapes showing much lower diversity than Mediterranean landscapes, which also contained lowest proportions of pine. My results from these suggests which landscapes were most conducive to easy fuel gathering, and which ones Neanderthals would have had to be most selective in to achieve regular fire regimes. From this, individual fuel-genera and site regimes are examined, which suggests diverse foraging regimes, ranging from fuel optimization to foraging optimization, with most combining both.

If fire was *essential* to survival, fuelwood availability would directly represent an area's carrying capacity. Given our assumed daily fuel consumption of 36.6-38.8kg per Neanderthal, exact maximum group sizes could be calculated. However, these study areas do not accurately enough represent any one site locale to determine how many Neanderthals it could have sustained. Given that fire was not necessarily essential, fireless Neanderthals could have survived in treeless regions, and even fire-using Neanderthals could have exceeded the maximum numbers if they used fire infrequently.

I: Foraging Experiment Methodology.

In order to replicate possible Neanderthal foraging patterns, I performed foraging exercises for wood in five different simulated environments. These experiments do not exactly replicate any particular site. Four represent different fuelwood-producing biomes, and one represents snow-covered winter landscapes. ‘Mammoth steppes’ surrounding many sites of course have no modern equivalent for experimental fuel gathering; it would probably correlate most closely with heathland/snowy biomes. This study relies on my own opinion of each fuelwood’s relative merits and its ease of foraging and transportation; however it was important that I personally undertook all of these foraging exercises, to standardise foraging practices across all biomes. When applicable, consent was previously obtained from relevant landowners. Studies were undertaken on dry afternoons (the exception being the Vilnius snowy biome, where it had been snowing), to mimic optimal wood-gathering conditions for driest deadwood. All tested foraging areas were unmanaged, with deadwood/standing snags in proportion to wild areas, and were not planted forestry areas which affect proportional representation of genera. An important difference to Neanderthal gathering areas is of course that my study areas were small isolated patches, within larger agricultural and/or development areas. This may have affected the diversity of genera recovered, as the only invasive species within the biome would be windblown seeds from agricultural areas, rather than other truly wild species from different locales. This may also have affected growth patterns, shapes, and growth of shrubs and ground-cover genera. I foraged without container technology or cordage for bundling, as all Neanderthals may not had access to this. Likewise, given that Neanderthals show great diversity in tools and there is no one universal “Neanderthal tool”, I did not cut branches with lithic tools, instead manually breaking branches or gathering deadwood. This practice was also easier than cutting branches with tools, and I believe would have been practiced unless deadwood was absent. The locations were as follows:

Table 10.1: the different study sites used in this foraging exercise.

Site	**Description**	**Date Sampled**	**Latitude (°N)**	**Average Temperature Range (C)**	**Average Precipitation Range (mm)**
Salthouse Heath, Norfolk, UK	Open heathland	September 2021	52.9	3 to 21	43 to 72
Walsingham, Norfolk, UK	Coniferous stand	February 2022	52.9	3 to 21	43 to 72
Cockthorpe Common, Norfolk, UK	Marshy wetland within riparian system	March 2022	52.9	3 to 21	43 to 72
La Roche de Solutre, Burgundy, France	Mediterranean-style open landscape	April 2022	46.3	0 to 27	18 to 82
Vilnius, Lithuania	Snowy coniferous and birch forest	November 2022	54.7	-7 to 23	40 to 80

I.I: Heathland.

Salthouse Heath is on acidic soil, with prevailing understoreys of bracken and ferns, containing common heather (*Erica cinerea*). Gorse (*Ulex europaeus*) formed low-level cover and higher c.2m growths, cut through with artificial access tunnels. The main trees were small stands of English oak (*Quercus robur*), isolated whitebeam (*Sorbus aria*), and some downy birch (*Betula pubescens*). Some heathland was grazed by Bagot goats and contains remains of WWII defensive structures. Consequently, these areas were avoided.

Figure 10.1: Salthouse Heath, showing concurrently-growing Sorbus and Quercus, and Quercus stands with deadwood on the ground, with an understorey of bracken. Photograph: Knight.

From the remainder, I found that initially, oak provided the most obvious deadwood. Large dry, debarked limbs had broken off these trees. These proved surprisingly difficult to break by hand, despite being dead for over a year. Those limbs over c.1m diameter frequently had missing or rotten corewood, and hard, solid sapwood exteriors. When broken, this most frequently created irregular fragments c.10cm diameter and 30cm long, limiting what could be carried without containers. However, these light, dry fragments proved excellent fire-starting fuels. Otherwise, oak provided few dead branches attached to trees within arm's reach. Oak also has slow turnover rates; ungathered areas provide abundant deadwood, but on returning in December 2022, no new deadwood was found, suggesting that this is a one-use resource, at least within annual timeframes. A single dead limb would fuel many fires, but these limbs do not regrow from trunks, and English oaks live for over 500 years. Except in immature oaks (which do not usually produce deadwood anyway), main trunks reach up c.1.5m before branching into a few large limbs, and smaller branches are inaccessible except via climbing. The primary source of deadwood is larger limbs snapping off, from which smaller branches are manually detachable; handaxes or other cutting technologies would not have greatly helped Likewise, cordage technology would not have helped, although containers (e.g. skin bags), would have helped with small but useful fragments. Oaks were found in clusters, providing shelter and spreading shade from sea winds and storms, and easily distinguishable from other genera. In the Middle Palaeolithic, mammoth, deer and boar foraging may also have impacted tree growth and created natural stands like these.

Whitebeam occurred as more isolated trees, more common than birch, and well-spaced enough to allow extensive undergrowth beneath them. They produced much less deadwood than oak, and this generally remained on the tree rather than fallen. The barked branches were straight, c.0.5-1m long. Some force was required to dislodge them, and clean breaks were harder to obtain, however the wood was easily portable. Whitebeam here was found on sides but not peaks of hills, which were bare. *Sorbus* may tolerate salt breezes better than some trees. Birch formed more isolated trees with very few fallen branches, and ones on trees only above breast height. Peeling bark was abundant, and large amounts could easily be obtained. If Neanderthals were shorter than me (6'2"), which is highly likely, they may have been unable to obtain *Betula* wood, although the bark would easily be obtained. Furthermore, the trees were very visible due to their distinctive bark, and easily distinguishable from other genera.

Gorse, although abundant, was not easily gatherable due to its spines. Neanderthals had no natural protection against these, and *Ulex* has no useful edible portions (excepting the flowers). Mature core wood reached a diameter of c.10cm, however this was only noted due to the artificial tunnels, whereas in wholly natural settings, thicker branches would be surrounded by spindlier, thorny ones. The only harvestable portion was where wildfires (or human accident) had already reduced some gorse spread, leaving hard but thornless semi-charred stumps and sections. Had Neanderthals set fires to clear landscapes (although this is debated by Daniau et al. 2010), this situation may have been achieved. The phenomenon is also long-lasting; as of the time of writing (February 2023), almost 1.5 years later, the area has not recovered, and the stumps were still easily accessible. Serrated sawing tools could have been useful, but handaxes and blunt force would have achieved little. The paucity of *Ulex* in Neanderthal fires suggests that they could not gather it except in these occasional pre-fired conditions, and even then with difficulty. Heather was found at low-level uniform spreads across open spaces rather than clustered. Living, blooming specimens were hard to break, limiting my collection to dead or mature specimens uniformly dispersed across the landscape. I could carry little mass, it being large volumes of small-diameter, spindly branches; however, it burnt extremely quickly, and would have been a valuable fire-starter.

In snow-covered landscapes with inaccessible or over-waterlogged low-level fuels, I predict that oak's utility would massively decline. Whitebeam would still provide fuel; birch would be accessible but rare, and use of low-level heather would also almost disappear. Gorse would be visible, but covered with snow and difficult to harvest. However, the warm climate and low altitude of this location prevented me from viewing it in snowy conditions.

I.II: Pine Stand.

The second area represents a monocultured Scots pine stand (*P. sylvestris*), surrounded by modern farmland, with nearby beech-dominated forests. This stand was originally planted, but had been unmanaged and unharvested for many years, developing abundant natural ungathered fuelwood and standing snags. The stand is found in a slight depression in the landscape, and understorey darkness has prevented significant colonization by other genera, although there has been no human post-planting intervention to prevent further colonization. Although interiorly monospecific, the stand's exterior also has several immature *Betula* and *Crataegus* trees and bushes seeded mostly by windborne colonization. The stand floor is coated with a c.5cm thick pine needle coating, decomposing and turning to humus at the bottom. The stand supports corvid colonies; feeding however on surrounding farmlands rather than the stand itself. If the stand extended further, it is unknown how much food could have been gathered from it by any species.

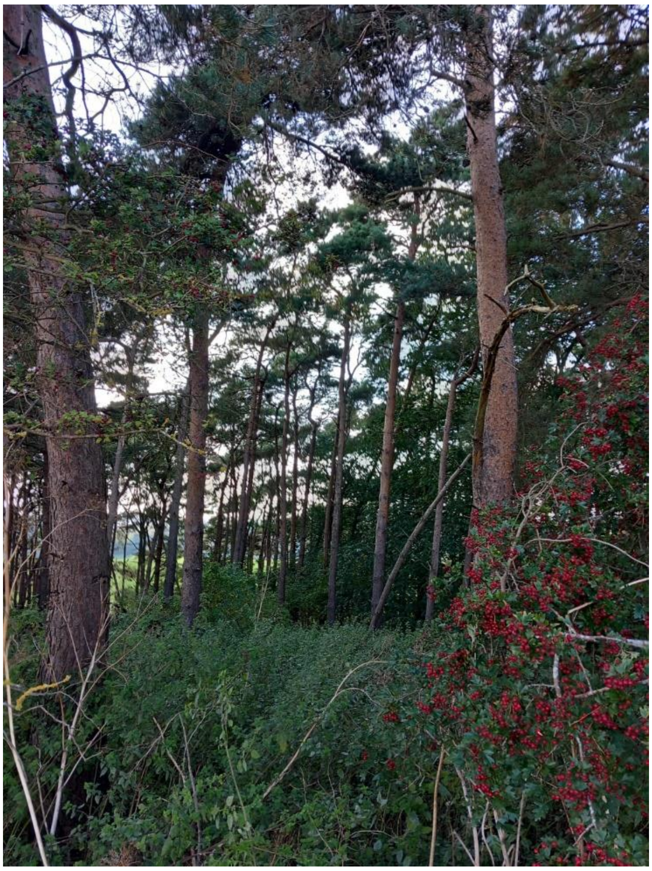


Figure 10.2: The pine stand showing the understorey, and invasive incursions of Crataegus. Photograph: Knight.

Only *Pinus* was harvestable here. Surface needles were already perfectly dry for c.2cm and provided abundant and valuable fuel, below which they decomposed and had much higher moisture contents. Without containers, gathering needles or cones is impractical; however with such technology, abundant fire-starting material would be easily procurable. Some gatherable branches retained needles, but not only were these living branches, but the needles were fresh and green, and less suited for burning. The total absence of small pine cones at Abric Romani Level J, despite abundant pine wood use, may result from their small size, whereas larger *P. picea* cones were burnt (Allue et al. 2017). This suggests that these Neanderthals lacked container technology, otherwise cone size would be irrelevant. Allue believe that large cones' value was for their pine nuts, as does Brown et al. (2011) for Gorham's and Vanguard's caves. Brown further suggests that cones were roasted to facilitate nut extraction, as noted ethnographically by Gale and Carruthers (2000). However I found that dry, dead *P. sylvestris* cones burnt well by themselves, provided that the scales had opened to allow oxygen influx into the interior. For Neanderthals with containers, cones would have been a valuable fire asset; and their presence could be used as a proxy to infer that these containers existed. Pinewood itself was abundant; the floor had many straight pieces approximately 0.5-1m long, of 5cm-15cm diameter. These all remained barked, although the wood inside was in varying states of decomposition. Likewise, many branches remained on the trees themselves, approximately 0.5m long, and well within arm's reach. The excessively straight and uniform wood allowed me to carry a lot in one journey; however, this wood property would also have made binding cordage technology particularly useful, and may have allowed me to either increase my carrying capacity, or carry wood in such a way as to free up my hands. The standing snags were approximately 1-2m high, rotten and easy to break and carry back larger single pieces. This wood's straight and uniform condition made carrying very easy, and I could carry a single 2m piece almost a mile back to the fire site.

I viewed this location in snow in December 2022, with a c.6-inch snowdrift across the landscape. However, this stand's closed and warmer nature prevented much snow penetration, and fallen waterlogged branches were still visible. Branches on the trees were not covered and still easily gatherable. Even the needle layer, beneath the snow, remained mostly dry and useable.

I.III: Wetland.

Cockthorpe Common represents a floodplain of the River Stiffkey, in North Norfolk, approximately 1 mile from its estuary. Surrounded by mixed arable and pasture land, the floodplain itself contains mostly willow (*Salix caprea*), with small admixtures of poplar (*Populus alba*), and invasive hawthorn (*Crataegus monogyna*) from surrounding hedgerows, although this survived poorly in the wettest areas. The river contains abundant fish, and the vegetation contained many nesting birds and smaller mammals. In the Middle Palaeolithic, such landscapes would represent important foraging locales, especially in the spring when this gathering took place. Eels also migrate across these wetlands, being easily harvestable with organically-woven eel traps, such as those found in Mesolithic Denmark (Fischer 2007). European eel is found in Neanderthal assemblages in Abri des Pecheurs, Abridos-1, Barasses II, Baume Moula-Guercy, Cueva Millan and Vaufray Cave (Guillaud et al. 2021). Unfortunately, these sites have not had charcoal tested to establish Neanderthal fire regimes within them. However, *Salix* would have provided ideal weaving materials for withy traps.

Figure 10.3: The wetland Salix growing in marshy pools, which was very difficult to gather. Photograph: Knight.

This wetland proved suboptimal for gathering fuelwood. Hawthorn formed small, hard, spiny bushes which were impossible to gather or transport back to camp. Willow formed abundant clumps of non-pollarded trees, growing in small pools and natural drainage ditches, with many easily-accessible low-level shoots, although they and the pools blocked access to main trunks and more mature branches. The wood was exclusively very green, and barked; it was extremely flexible, but could be broken crudely by hand, although with frayed, broken ends. Incisive stone tools would have proved useless. I could carry many of these thin, straight, flexible withies at once. Cordage would have greatly assisted me carrying them, as with the pine in the previous site; however here, the wood itself, or its thin bark strips, could easily have been used as cordage itself without requiring any extra-biome materials, or particular ropemaking or knotting skills. The wood itself however, without extensive drying, burnt at low temperatures, released much moisture and did not catch easily.

The poplars were planted alongside the watercourse many years ago, but had not been tended since then, and had created abundant deadwood. Their position very close to the riverbank, possibly an artificial anomaly due to human plantation, would have caused much of their deadwood to fall into the stream and either be difficult to recover or have been carried away. The remainder fell as small branches, and no accessible dead branches remained attached to the trunk. Occasionally entire trees had fallen, occasionally over the stream, frequently remaining at least partially alive and releasing new branches at new angles. These were easily gatherable, almost as a form of natural pollarding, creating abundant living branches. Fresh *Populus* however likewise was not easily-ignitable, being like *Salix* very smoky and slow to catch, although forming larger fuelwood pieces.

In December 2022, this locale experienced extreme cold weather, although without snowfall. Nonetheless, many pools froze, aside from the main river channel, which made wood recovery extremely unpleasant, and would have greatly reduced this biome's overall foraging potential; although breaking through the ice would never have proved life threatening (aside from potential hypothermia). Given their "poor" qualities, why would Neanderthals burn this biome's woods, especially *Salix*, as fuels? Allue et al. (2017) hypothesise that certain low-level fuel genera in Abric Romani, including *Salix*, could represent "accidental burning of wooden objects, and not specific use as fuel" (p.11). If Neanderthals wove willow withies, they would have particular utility in this biome as fish traps. However, these would remain partially submerged and would have not dried out and improved its burning qualities any more than fresh stem specimens. Likewise, it is probable that these larger organic structures would have been repaired in-situ rather than in caves. *Salix* may have been carried into caves as part of woven cave structures, either subdividing living spaces or acting as entrance windbreaks, for which we have no direct evidence. Useless broken structures would eventually be dry and suitable to burn. This can explain the small *Salix* presences at the following 19 levels:

Table 10.2: comparing the prevalence of Salix/Populus in Middle Palaeolithic sites where it is present <5% in the charcoal.

Site and Level	**Proportion of *Salix/Populus* charcoal (pre-calibration, all <5%)**
Abric Romani Zone IV	0.05
El Salt Unit Xb AFA 1	0.13
El Salt Unit Xb AFA 2	0.26
Cova Gran S1B-S1F	0.38
Cueva del Camino Level V	0.4
Abric del Pastor Unit IVc	0.45
Klissoura Layer VIII	0.48
Abric del Pastor Unit IVd	0.51
Pod Hradem Level 11	0.58
Klissoura Layer XVII	0.75
Cueva Anton Complex AS5	0.9
El Salt Unit Xa	0.98
Pod Hradem Level 9	1.8
Theopetra Layer II7	2
El Salt Unit IX	2.96
Bojnice III Layer IX	3.31
Cueva Anton Complex AS2	3.39
Llonin Level VIII, CP, VI Gal	3.68
Cueva del Conde Level N20A	3.83

However, four sites show *Salix/Populus* in higher proportions than expected from burning old useless wooden structures; Kaldar Layers 4-5 (11.76%), La Vina Levels XIIIbas, XIV, XV, I.A, I.B (13.15%), Scladina Unit 4A (6.41%), and Theopetra Layer II11 (9%). These might represent different fire regimes where these genera were used as core firewoods. Perhaps in these ecosystems, seasonal fluvial risings and fallings might expose these woods as driftwood at certain seasons, naturally drying them and creating valuable fuels without anthropological intervention.

I.IV: Mediterranean Landscape.

The fourth study area, by the famous Roche de Solutre in France, represents mixed dry Mediterranean scrubland typical of many southern Neanderthal caves. Fringed by cultivated scrublands, and on small dry hills in Burgundy, it has many open areas between rocks; the under-storey is primarily composed of mature box (*Buxus sempervirens*) and broom (*Cytisus scoparius*) plants, each uncultivated. The trees are a mixture of olive (*Olea europaea*) and juniper (*Juniperus communis*). There are also occasional vines (*Vitis vinifera*) from neighbouring vineyards; this cultivar was however disregarded. Box and broom coexisted in the same stands, forming bushes 1-2m high and very dense undergrowth, through which small paths wound. I saw few animals except lizards and birds in this biome, but it does support large populations of wild boar (*Sus scrofa*), although farmland doubtless also supports their foraging today. Box proved an exceedingly hard wood, with no dead specimens noted, and was ungatherable without sawing tools. *Buxus* is common at a low level in Neanderthal fires, found in 7 levels.

Figure 10.4: La Roche de Solutre; this foraging was undertaken in a similar nearby scrub landscape.

Photograph: Knight.

Table 10.3: comparing the prevalence of Buxus in Middle Palaeolithic sites where it is present <5% in the charcoal.

Site and Level	**Proportion of *Buxus* charcoal (pre-calibration, all <5% charcoal)**
El Salt Unit VIII	0.3
El Salt Unit IX	0.74
El Salt Unit Xb AFA 1	0.78
El Salt Unit Xb AFA 2	1.32
El Salt Unit Xb AFA 3	1.63
Cova 120 Level VI	2.06
Les Canalettes Level 4	2.09

Boxwood is a very good tool material, with a high tensile strength. Although not directly surviving as tool-hafts in Neanderthal sites, it has been found at the Neolithic site of La Draga (Pique et al. 2018). As with *Salix* in wetlands, boxwood burnt in these sites could result from disposing of used tools. However, it is found in higher proportions at Les Canalettes Level 3 (5.04%) and Abri du Maras Layer 4 (6.9%), and greatly higher at Les Canaelettes Level 2 (22.93%), Riparo Bombrini Stratum IV (25%) and Teixoneres Cave Levels II, IIb and III (28.57%). The latter three cannot be explained except by boxwood being a staple fuel. Its procurement is a mystery, as collecting sufficient box fuelwood would have been very difficult; perhaps certain other biomes create more deadwood from declining mature *Buxus* stands, or wildfires such as with gorse may expose the wood further. Boxwood is immediately recognizable, although potentially confusable with other evergreen bushes (e.g. *Eunymus*).

Broom was widespread alongside Box. This plant also has thick, inflexible and ungatherable main branches, but had gatherable younger flowering stems, unlike Box. These were not an ideal core fuel, but made an excellent fire-starters, as the flowers catch easily. In flowering months (April-June), *Cytisus* was instantly recognizable, visible from some distance away.

Olive and juniper trees in this biome were scattered mature specimens, with no deadwood found around them, and few attached dead branches. This may of course result from French foraging laws, whereby much more private fuelwood foraging occurs, and less deadwood remains than in corresponding English forests. However, I saw no recently-broken branches. Both trees grow slowly, producing little deadwood. Such a development was unexpected, given the propensity of both these genera in many layers at Klissoura Cave:

Table 10.4: comparing the prevalence of Olea in Middle Palaeolithic sites where it is present >20% in the charcoal.

Site and Level	**Proportion of *Olea* charcoal (pre-calibration, all >20% charcoal)**
Klissoura Cave Layer XVII	23.31
Klissoura Layers XXd-c	24.56
Klissoura Layer XXb-a	24.66
Klissoura Layer XXg-XXe	28.57
Klissoura Layer XXI	41.27
Klissoura Layer XVIII	61.9
Klissoura Layer XIX	73.13

In six other levels of this and other sites, low incidences suggests either expedient collection of rare deadwood, or burning of olivewood tools, but Klissoura's high levels suggests entirely different local foraging routines. Neanderthals here may have uniquely felled living olive trees for wood, as I cannot imagine how else to obtain sufficient quantities of this wood; especially when oak was always available as another potential deadwood source. More permanent Neanderthal occupation here may have exhausted oak deadwood resources, necessitating felling of (other) living trees. This biome had the least deadwood of any studied, but living specimens were all dense and dry, and would have burnt better than living specimens from elsewhere. Juniper shows similar patterns:

Table 10.5: comparing the prevalence of Juniperus in Middle Palaeolithic sites where it is present >20% in the charcoal.

Site and Level	**Proportion of *Juniperus* charcoal (pre-calibration, all >20% charcoal)**
Theopetra Layer II11	35
Riparo Bombrini Stratum IV	37.5
Klissoura Layer XII	40.16
Klissoura Layer VIII-VII	40.74
Cueva Anton Complex AS2	45.76
Klissoura Layer XI	49.64
Abric del Pastor Unit IVc	56.47
Abric del Pastor Unit IVd	69.92
Theopetra Layer II10	96

Aside from these five sites however, 35 layers show juniper charcoal in much lower proportions, suggesting occasional foraging routines for deadwood. However, in these five sites, as with olive, whole juniper trees must have been burnt to fulfil the quantity found here.

I.V: Snowy Forest.

The final study area, near Vilnius in Lithuania, represented northern European woodlands in wintry conditions. Here, snowfall had completely obscured fallen deadwood, limiting accessible fuel to standing snags and dead branches still attached to trunks. This woodland was composed of pine (*Pinus sylvestris*), Norwegian spruce (*Picea abies*) and larch (*Larix decidua*), with a few isolated birch stands (*Betula pendula*) in open country. The snowdrifts of c.2 feet depth meant that understorey compositions could not be determined; however, as none appeared above the snow, it would have been inaccessible to Neanderthals anyway.

Figure 10.5: The easily-distinguishable Betula in the snowy landscape, albeit with few easily-gatherable branches. Photograph: Knight.

Pine once again proved to be the best fuel available; abundant attached dead branches meant that most trees provided abundant fuelwood even when snowdrifts obscured the floor. The wood appeared rottener and more waterlogged than its warm-weather Norfolk counterpart, but retained relatively dry bark. The reliance on only gathering attached branches meant that branches tended to be shorter than those in Norfolk, but of similar diameters. No standing snags were observed; if they did exist, there is no reason why they should not be as useful and portable as those in the other pine forest. If there was a needled forest floor, it was invisible here, and would not have been easily accessible for foraging; the snowfall here was much higher than in the Norfolk study, and the trees further apart.

The larch here was from elderly stands of mainly dead trees. From this, it is difficult to extend inferences to healthy stands; but in this condition, larch provides fuel with similar morphologies to pine branches. There were similar abundances of dead branches on trunks, but they were rottener and often split during transport. Larch did however provide more smaller twigs and branches attached to larger ones than pine, where sub-branches had already been lost. This could have been especially valuable in fire-starting, as would larch cones. Many cones remained attached to dead branches, which could be bundled with branches without container technology. This larch wood proved inferior to pine when burnt, being somewhat rotten and smoky.

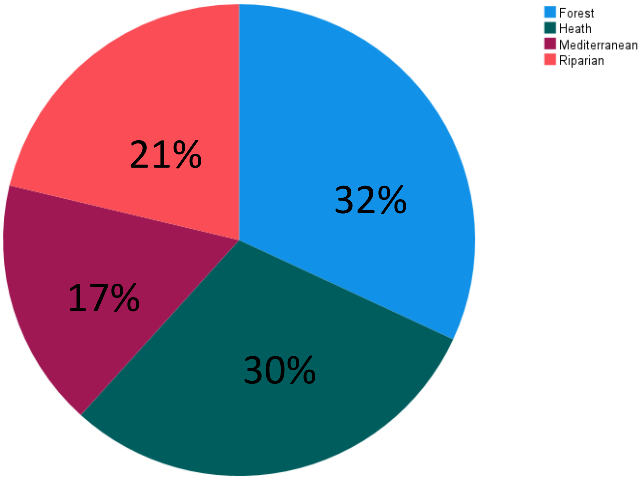
Norwegian spruce, however, proved difficult to collect. Downwards-pointing branches retained needles to low heights, and consequently up to half a foot of snow had piled up on these branches. Removing this was unpleasant, and branches beneath were young and healthy, with green needles, flexible rather than snapping although smaller branches could be harvested. Using handaxes would not have helped, although modern sawing tools would of course have been beneficial. These smaller branches proved bad as fuels, with high moisture and resin contents creating high ignition temperatures.

Birch functioned very similarly to that in the first study, with few dead branches but abundant bark. In this low-temperature landscape, with few grasses or conifer needles, birchbark would have been even more important for fire-starting. In snow, *Betula* was very distinctive, very distinguishable from conifers despite the white landscape, and easily identifiable and exploitable by Neanderthals.

II: Neanderthal Site Biomes.

Based on anthracological data, combined with palynological and micromammal studies, the surrounding landscapes of most Neanderthal sites have been previously studied. Whereas sometimes agreement is reached on a particular landscape (e.g. the thermophilious Mediterranean open landscape around Gorham's Cave), often landscapes vary both temporally and spatially. In particular, heathland and forested landscapes frequently succeed one another (Study Area 1 succeeding to 2 and 5, or vice-versa) within similar climatic conditions. Whilst forests can uniformly spread across large areas, open 'heathland' may also have many isolated stands of trees, most resembling Study Area 2, within open areas. Even my heathland study contained small oak copses. Rapid glacial and interglacial cycles mean that single sites experienced varied conditions. Neanderthals may additionally have chosen sites deliberately situated between different biomes, to take advantage of each. Riparian wetland systems in particular would be common to many Neanderthals, as rockshelters are carved out by fluvial action within valleys; however by rivers' limited linear nature, Neanderthals would of course have had to exploit other systems than these. The question is which ecosystem(s) they particularly exploited for fuelwood. They are unlikely to have gathered from just one system, and may have exploited many. Bojnice III, for instance, shows remarkable co-gathering routines in wet riparian landscapes, where Neanderthals simultaneously unearthed raw lithic materials from river sediments, and also collected and burnt nearby *Salix/Populus* (Neruda and Kaminska 2013). Simultaneously, they also burnt *Pinus* and *Picea/Larix* from isolated conifer stands.

Single sites may frequently represent two or more biomes, most usually heathland/forest/wetland overlapping. This is especially prevalent if sites span long time periods, with drastic vegetation change during its occupation. The following site assessments can be made (Graph 10.1), based on comments in the papers cited in Chapter Eight, p.211, where the authors attribute surrounding environments to one (or more) of these landscape types. This attribution is mostly through arboreal tree types, sometimes strengthened with additional micromammal or herpetofaunal analysis.



Graph 10.1: The proportions of different biomes found around Neanderthal sites with analysed anthracological diagrams. The biomes were determined by the papers that analysed the sites (references in Chapter Eight, p.211). Similar prevalences of forested and open environments suggests that one succeeded the other, and that both were important Neanderthal foraging spaces. The relative lack of Mediterranean open sites may suggest that this was a more challenging foraging biome or that there were just coincidentally fewer fire-using sites in these landscapes.

The proportions are calculated by assigning each site equally rated values for each biome they were believed to have been in, regardless of the proportion of wood gathered from each biome. In practice, riparian zones would have had much less wood gathered from them, and potentially much less time spent in them, as *Alnus/Salix/Populus* charcoal values are normally <5%. However, this chart represents the relative *accessibility* of each biome to Neanderthals, regardless of how much each was *actually* exploited for firewood. This only represents the spread of biomes for Neanderthal sites with published charcoal diagrams. The biomes themselves across the whole of Europe may have been more randomly spread, frequently limited by natural cave site locations.

Given that these biome proportions represent the number of fire-using sites in these biomes (with identifiable charcoal) rather than all sites, these biome proportions may also indicate how easy Neanderthals found gathering firewood in each landscape. Biomes with many fire-using sites in them may be the easiest to gather wood in. This does somewhat match my own experiences foraging in the various environments. The Mediterranean landscape had the least available wood, and was the least wooded. Wetness caused minimal problems, but wood hardness and a lack of deadwood from Mediterranean-type trees caused issues instead. I did not note any more natural wildfires here than in other study areas (the only wildfire noted was in the heath area) to expose more half-charred wood or natural charcoal to burn. However, given that this and all areas were somewhat near human habitation, any natural wildfires would be extinguished as soon as possible in my sample areas. Consequently, only 17% of fire-using sites are in Mediterranean biomes. Riparian biomes are more common, accounting for 21% of sites; however their relative prevalence may be primarily influenced by caves, being overwhelmingly found in river valleys. Wetland systems were general foraging locales, but Neanderthal fires contain correspondingly low levels of riparian trees, despite these being widespread across many sites. Open and forested landscapes have similar prevalences, reflecting equal ease of gathering in each, and their interspersion within mosaic landscape systems. When we correlate proportions of genera burnt across sites in different biomes are correlated, the following patterns appear:

Tables 10.6-10.9: comparing the proportions of different genera found at the four different site types: Heath, Forest, Wetland, and Mediterranean, respectively.

Genus	**% Charcoal Assemblage**	**Recalibration for 350°C Burning**	**Percentage of Heath (Open) sites at which this genus is found**
Pinus	63.08	60.97	93%
Picea/Larix	10.06	9.09	14%
Betula	6.30	8.26	57%
Prunus	4.42	4.42	43%
Buxus	3.31	3.42	21%
Quercus	3.05	3.69	50%
Juniperus	2.58	2.42	50%
Sorbus	2.21	2.47	21%
Salix-Populus	1.56	1.83	50%

<1%: *Acer, Carpinus, Castanea, Crataegus, Erica, Fagus, Ficus, Fraxinus, Hedera, Olea, Pistacia, Pyrus, Rhamnus, Sambucus, Ulmus.*

Genus	**% Charcoal Assemblage**	**Recalibration for 350°C Burning**	**Percentage of Forested sites at which this genus is found**
Pinus	60.37	59.78	87%
Picea/Larix	10.44	9.66	20%
Juniperus	6.58	6.33	67%
Quercus	5.22	6.47	73%
Buxus	4.8	5.08	40%
Prunus	3.8	3.89	47%

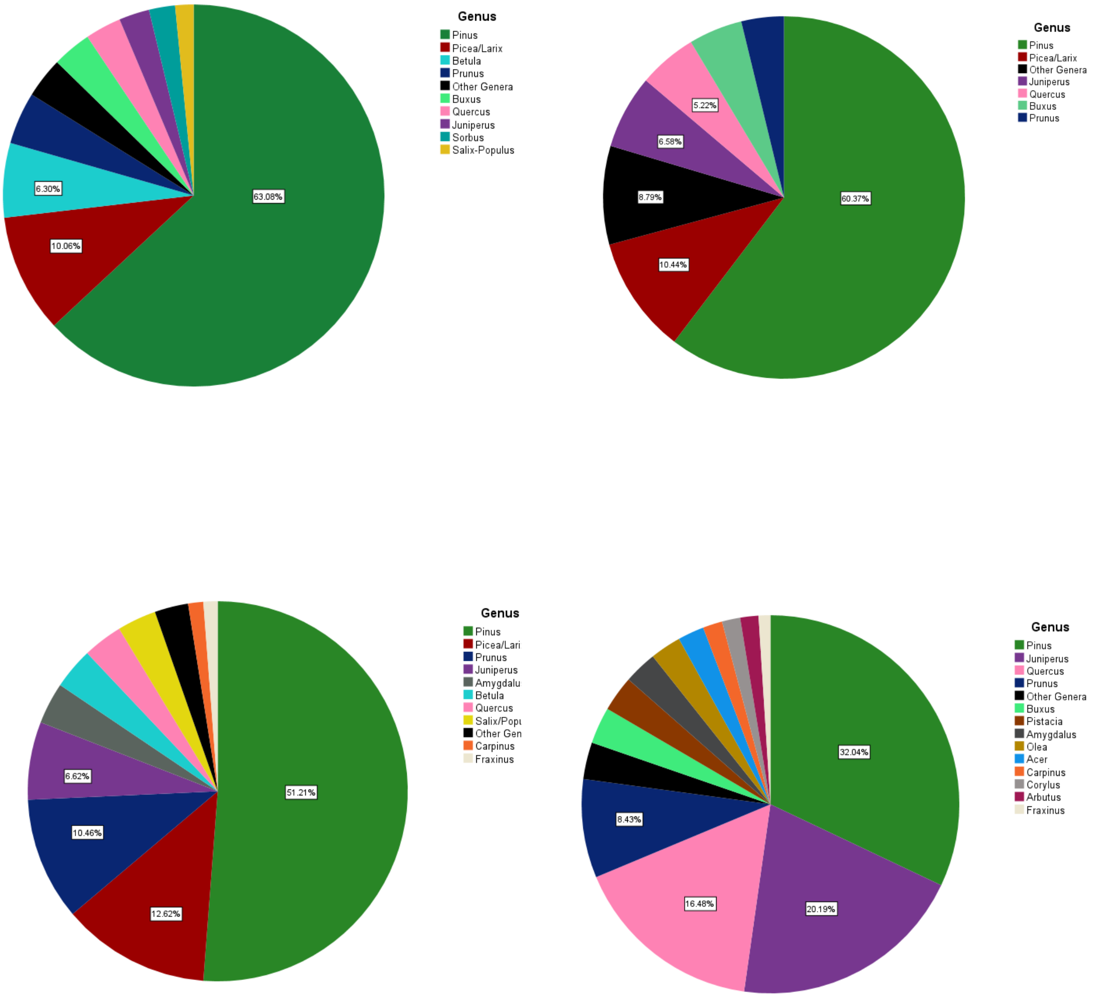
<1%: *Acer, Arbutus, Betula, Carpinus, Celtis, Cornus, Corylus, Erica, Fagus, Ficus, Fraxinus, Hedera, Hippophae, Juglans, Olea, Phillyrea, Pistacia, Pyrus, Rhamnus, Salix/Populus, Sambucus, Sorbus, Ulmus, Viburnum.*

Genus	**% Charcoal Assemblage**	**Recalibration for 350°C Burning**	**Percentage of Riparian (wetland) sites found at**
Pinus	51.21	49.47	80%
Picea/Larix	12.62	11.39	20%
Prunus	10.46	10.46	50%
Juniperus	6.62	6.21	70%
Amygdalus	3.53	3.95	10%
Betula	3.51	4.60	30%
Quercus	3.37	4.07	60%
Salix/Populus	3.32	3.89	90%
Carpinus	1.29	1.61	10%
Fraxinus	1.21	1.48	30%

<1%: *Acer, Arbutus, Buxus, Corylus, Erica, Ficus, Hedera, Olea, Phillyrea, Rhamnus, Sambucus, Ulmus.*

Genus	**% Charcoal Assemblage**	**Recalibration for 350°C Burning**	**Percentage of Mediterranean sites found at**
Pinus	32.04	29.55	63%
Juniperus	20.19	18.08	88%
Quercus	16.48	19.02	63%
Prunus	8.43	8.05	50%
Buxus	3.13	3.09	13%
Pistacia	3.05	3.24	25%
Amygdalus	2.83	3.02	13%
Olea	2.65	2.78	25%
Acer	2.25	2.57	13%
Carpinus	1.67	1.99	25%
Arbutus	1.56	2.04	13%
Corylus	1.56	1.83	13%
Fraxinus	1.01	1.18	38%

Under 1%: *Erica, Laurus, Salix/Populus, Rhamnus, Sambucus, Taxus, Ulmus*



Graph 10.2: comparing the proportions of different genera found in the fires of sites in the different landscape types. Clockwise from top left: Heath, Forest, Mediterranean, Wetland. Notably, Mediterranean biome sites contain significantly less pine and more juniper and oak than other site types, and forests contain a higher proportion of other genera, suggesting more expedient foraging there.

Foraging routines for heathland and forested colder landscapes are extremely similar; pine is the dominant fuel, followed by larch and spruce. The only difference is that in forests, proportions of seldomly-used (<1%) fuelwoods, representing possible expedient use when preferred fuels were unavailable, is much higher, at 8.79%, compared to 3.43% of open landscapes. This may be due to availability, if sheltered forests allowed more fuelwood genera to grow and be exploited. Alternatively, lower prey biomasses in forests could have forced Neanderthals within them to forage over longer distances than their open landscape counterparts, thus have them encountering more fuelwood genera to occasionally burn. In riparian systems, pine use slightly declines, and cherry and willow exploitation increases, as expected given they are riverside trees. In Mediterranean biomes, fuel gathering routines are entirely different; although pine still dominates, it is supplemented much more by juniper and oak, which were relatively minor genera in other biomes.

As aforementioned, I found it harder to gather fuelwood in the replicated Mediterranean dry biome than in any other, although of course my study area does not by any means replicate all Mediterranean biomes, (e.g. closed dry oak forests). If Neanderthals lacked fuelwoods in these biomes, or if available fuelwoods were suboptimal, these hominins may have been less likely to make fire. Such areas would of course have absolutely *required* fire use much less than colder areas. Based on the calculations for duration and heat output in Chapter Nine, the (average) fires in the different biomes can be thus categorized following the 350°C recalibration, again proportional to *Pinus* = 1.

Table 10.10: comparing the burning qualities of the fires in the different biomes. Despite different genera fuel inputs, there is little differences between these, except that forest and Mediterranean biome fires seem to emit less light than open landscape and riparian ones.

Type of Site Biome	**Average Maximum Temperature of Fire**	**Average Duration of Fire**	**Average Light Emitted**	**Percentage of Assemblage where Average Temperature/Duration values are used**
Heath Landscape	0.9848	0.9777	1.203	16.16 (17.99 for light emitted)
Forested	0.9862	0.9948	1.0849	24.09
Riparian	0.9769	0.9903	1.1902	23.49 (28.99 for light emitted)
Mediterranean Dry	0.9731	1.0444	1.1016	43.33 (50.25 for light emitted)

In each, large proportions have been calculated from averages, making the results less accurate. However, the values appear similar between all biomes, suggesting that landscape type did not affect fire quality. In Chapter Three, there was no difference in fire frequency between northern and southern situations; however this does not take biomes themselves into account, as even southern sites could be cold in glacial periods. Without finer-grained data, it is impossible to tell whether warm-biome Neanderthals used less fire than cold-biome ones; they almost certainly had to work harder for those fires they had.

The overall inferences here are only products of subjective gathering experiences by myself; Neanderthals foraging in identical landscapes may have looked for very different properties in wood, and/or had different foraging strategies. Their landscape-use may have been dominated by lithic resource availability or food gathering instead; trees may have been selected to burn as by-products because the bark was also edible (or used medicinally as with *Salix*). Trees may have been visited because particular birds or insects frequented them, or because prey species ate their young buds, or drank from nearby water sources, and fuelwood was just a byproduct. Furthermore, my recognition of different genera was based on my prior scientific knowledge, my reasoning for where they were expected to grow, and ability to distinguish genera-specific morphological features of the trees. Neanderthals could almost certainly discern colour as well as us, but if they did not discern specific tree-specific morphological features such as leaf shape, bark patterning etc., then they may not have foraged by genus, or regarded genus as an important criterion. Nonetheless, difficulty/ease of gathering and fuel quality would depend on the fuel genus, even if Neanderthals did not recognize genera-specific contributions to this. My foraging areas replicated those which Neanderthals would have frequented, and if they used fires at all regularly, they would have foraged for wood at least as part of other expeditionary trips, if not for exclusive fuelwood-gathering trips.

III: Foraging Practices and Choices.

With regards to those genera burnt, Scots pine (*P. sylvestris*) in my experiments was the easiest species to forage for. It was immediately distinguishable from other trees (aside from perhaps spruce/larch growing in close mixed stands); dry deadwood was abundant, in very regular, easily-portable pieces. Oak seems another optimal genus, with large, dry limbs, although less straight and regular than pine. A disadvantage was that oak deadwood was rarely on the forest floor, more frequently above arm’s reach in the trees. If Neanderthals had longer occupation durations, oak deadwood supplies might easily be exhausted. Birch was also abundant; although harder to gather as large branches, birchbark (for firestarting) would have been abundant. Birch smoke is also antiseptic and could have been used to repel mosquitos and fumigate caves (Uzquiano et al. 2008). Sometimes convenience mirrors optimization; these wood types are simultaneously “good fuels”, as defined by burning qualities, and also easily harvestable and abundant. In such areas, it would be very hard to determine motivations behind such fuel choice; comparisons with pollen records might be telling, and also especially what other trees are available in the landscape, and how good they are as fuels.

Selection towards pine in pine-dominant landscapes (e.g. Cova de Coll Verdaguer) might indicate recognition of pine's good foraging and burning qualities. At Gorham's Cave, Neanderthals chose pine when juniper was the dominant landscape tree. As juniper is very difficult to forage, selection of pine here probably suggests selection for its ease of gathering. At Cueva del Camino however, Neanderthals also had abundance hazel and alder available, which have many branches available to easily collect; preferential pine use instead suggests selection for its burning properties. Abric Romani presents a mixed model; Zones V and III are in pine-dominated landscapes, with some juniper and oak, and purging buckthorn in Zone III. Selection against juniper results from its difficulty in gathering; however oak, if available, both burns well and is easy to collect. Their not utilizing it much here might suggest very low deadwood levels per living oak tree (no recent storms to produce it, or recent wildfires removing it), or selecting for pine for specific burning qualities. Bolomor Cave likewise shows surprising selections against oak, given large (>25%) presences of oak in the landscape. Riparo Bombrini, on the other hand, is the most surprising as it shows a strong landscape presence of pine (>80%), but a complete absence of it from the charcoal record, instead focusing on seemingly odd fuelwoods such as *Arbutus, Buxus, Corylus, Erica* and *Juniperus.* All these woods would be harder to gather than pine, and their selection can only be reasoned for that their burning properties were somehow optimized for Neanderthal functions, or that these Neanderthals had no fuelwood selection criteria. None of these woods were tested by Hoare or Thery-Parisot; however, box and juniper, both being dense, may be slow-burning. However given the abundant local pine, I cannot imagine that a lack of fuelwood overall would have *necessitated* long-burning fuels and fewer trips; this use of this sort of fuel must have been a conscious choice to minimize numbers of foraging trips.

The vast majority of the (anthracologically) studied sites however do not have corresponding pollen diagrams, so selection processes for particular properties is unclear. Certain Neanderthals may have been smarter than others; and burning fuels scoring low in Hoare's (2020) burning traits does not necessarily mean that these same fuels were easy to gather. However, if all groups optimized in some way, then selecting hard-to-gather fuels with one or more good burning traits suggests optimization for fuel properties. Selecting fuels which rank low on Hoare's burning traits (but may have had other unknown good properties), but which are easy to gather, suggests optimization for foraging properties. Selecting high-ranking and easy-to-gather fuels could suggest either or both models, and is especially the case with pine and oak fuels. And finally, selecting low-ranking and hard-to-gather fuels can either suggest 1) particular unusual uses for that fuel which were not considered by Hoare, 2) inexperience with fire, or 3) odd landscape patterns where such fuels could be gathered more easily than usual.

Table 10.11: comparing the quality of fuelwood genera versus their ease-of-gathering.

Quality	**Easy to Gather**	**Hard to Gather**
High-Ranking Fuel	*Larix, Pinus, Quercus*	*Betula*, Buxus, Crataegus, Erica*, Juniperus, Olea, Picea, Ulex*
Low-Ranking Fuel	*Alnus, Populus, Sorbus*	*Cytisus, Salix**

* these woods are made much easier to gather with bundling/container technology, as they form masses of smaller branches/twigs.

Difficulties in distinguishing morphologically-similar charcoals means that *Larix-Picea,* and *Salix-Populus,* are often grouped, an unhelpful distinction given that one of each of these is hard and one is easy to gather (although each within a group share burning properties, suggesting that burning properties and charcoal morphological characteristics go together). However as mentioned on p.291, Kaldar and La Vina Neanderthals burnt relatively high proportions (11% and 13% respectively) of *Salix* alone, a hard-to-gather and hard-to-burn fuel. This strongly suggests Neanderthals collecting fuelwoods irrespective of foraging costs to fulfil some immediate need. It could be for *Salix*'s smoking properties, a lack of prior preparation on the part of the Neanderthals, exceptionally adverse circumstances (harsh winters) or ignorance of fire use. Expediency could also be suggested from using wider ranges of less-common fuels, suggesting indiscriminate gathering in very localized areas; although the range of fuelwoods used is of course also determined by how long sites were used for, and how much vegetation change there was during this time. This is the case in Cueva del Conde Level N20A, where many different rarer woods were burnt in lower proportions, including *Arbutus, Castanea, Crataegus, Cytisus, Erica* and *Ulex* (although these last three may have been firestarters). This level evidences burning of 15 different genera, 11 of which formed under 2% each of the charcoal record, contrasting strongly with the slightly earlier Level N10, where only 8 genera were burnt, with only 3 forming under 2% each. This suggests that the later Cueva del Conde Neanderthals used a much wider range of fuelwoods, although whether this was through experimentation or expedient needs is uncertain. Les Canalettes Neanderthals likewise burnt 13 genera in Level 2, including *Corylus, Fagus, Juglans, Pyrus* and *Sorbus,* but those in Level 4 only burnt 7 different genera, and no unusual ones amongst those.

Most Neanderthals burnt high-ranking and easy-to-gather fuels; however juniper and olive, hard-to-gather slow-burning fuels, dominate in Abric del Pastor, Klissoura and Theopetra (Layer II10). Given that both *Quercus* and *Pinus* were alternatively available in Abric del Pastor and Klissoura, Neanderthals here may have valued *Juniperus'* slow-burning and consequently labour-saving qualities. If, as above, using wide varieties of rare woods in a site suggests expedient gathering or inexperience, conversely burning few (good) fuelwoods may instead suggest the reverse. Some layers utilizing only three or fewer fuelwood genera are listed below:

- Abri du Maras Layer 4 burns *Buxus, Juniperus* and *Pinus* (dominant) – multifunctional pine here is complemented by slower-burning woods possibly chosen to burn overnight.
- Aguilon P5 burns *Pinus* (dominant) and *Prunus* – minor supplementations of *Prunus* may be expedient gathering as it neither ranks particularly highly nor is especially easy to gather. Aguilon might represent a site of wholly expedient gathering, possibly masked by the fact that pine, immediately available, is also an optimal fuelwood.
- Bolomor Levels XI and XIII burns *Juniperus* and *Pinus* (dominant) – similar to Abri du Maras.
- Cova 120 Level V burns *Juniperus, Pinus* (dominant) and *Ulmus* – another similar pattern although burning and gathering properties of elm are currently poorly-known.
- Cueva Anton Complex AS2 burns *Juniperus, Pinus* (dominant) and *Salix/Populus* – juniper and oak occur in such similar quantities that this may represent pine gathered for ease-of-foraging and juniper gathered for its slow-burning properties, in almost even proportions, or alternatively half expedient and easy pine fires and half better-prepared juniper fires. *Salix-Populus* may represent expedient gathering.
- Kaldar Layers 4-5 burns *Amygdalus, Prunus* (dominant) and *Salix* – we do not know the burning and foraging properties of the two former; however unusually high proportions of *Salix* gathered here may suggest expedient gathering of all three.
- Llonin Cave burns *Betula, Pinus* (dominant) and *Salix* – very high proportions of birch (31.29% of all charcoal) suggests that high-quality fuels were gathered at high foraging costs, the shortcomings of this practice being filled in with occasional *Salix*.

- Nesher Ramla burns *Pistacia, Prunus* and *Quercus* (dominant) – the unknown qualities of the two former woods means we cannot understand why they were gathered.
- Pod Hradem Level 11 burns *Picea/Larix* (dominant)*, Pinus* and *Salix/Populus* – this suggests regimes of almost exclusively gathering high-quality fuels (as low-quality *Salix/Populus* forms only 0.58% of the charcoal assemblage) – if *Picea/Larix* is larch, this also represents easy gathering, but with a greater foraging cost if spruce.
- Teixoneres Cave burns *Buxus, Pinus* (dominant) and *Quercus* – similar patterns to Abri du Maras.
- Theopetra Layer II3 burns *Carpinus, Fraxinus* and *Prunus* (dominant) – although the foraging properties of these woods are unknown, *Carpinus* is exceptionally slow-burning and *Fraxinus* emits lots of light, suggesting that these are high-quality fuels.
- Theopetra Layer II8 burns *Fraxinus, Prunus* and *Quercus* (dominant) – similar patterns to Layer II3.
- Theopetra Layer II10 burns *Juniperus* (dominant) and *Prunus* – dominating *Juniperus* suggests particular planned regimes for longer-burning but harder-to-forage fuels.

It is notable that of these layers burning few fuels, only two are *Prunus*-dominant (Kaldar and Theopetra Layer II3) and one *Juniperus*-dominant (Theopetra Layer II10); the remainder are dominated by exclusively high-ranking, easy-to-gather fuels (*Larix, Pinus* and *Quercus*). This further suggests that Neanderthals could recognize these core fuels which were both expedient and high quality. Alongside them they either utilized specific fuels fulfilling particular combustion niches which the core fuels could not fulfil (e.g. adding slower-burning fuels for overnight smouldering for Abri du Maras, Bolomor, Cueva Anton and Teixoneres), or utilizing further fuels at random.

IV: Conclusion.

This chapter has addressed the flipside of wood burning qualities; foraging qualities, in terms of deadwood accessibility and portability across many landscape types. Although ease of gathering is landscape- rather than genera- specific, nonetheless the exclusivity of certain genera to certain landscapes means that certain woods are easier to gather than others. Anthracological records show that heathland and forested landscapes had very similar proportions of genera, although forests were more diverse, but Mediterranean landscapes contained much less pine and more juniper and oak. Wood burning qualities, in terms of projected burning duration, light output and temperature, varied minimally between biomes, suggesting that no Neanderthals had advantage over others regarding biome-specific fuel quality. However, those in wetland and Mediterranean biomes were disadvantaged in terms of ease of gathering, and fires may have been harder to fuel.

Some woods such as *Salix* lacked deadwood but were easy to transport once cut; others such as *Betula* and *Quercus* were easy to gather when available, but had limited deadwood presences, and others such as *Larix* and *Pinus* were universally easy to gather as deadwood and were also easily carried. The two dominant genera throughout Neanderthal fires, pine and oak, are both high-quality fuels and also easy to forage (provided that intense site occupation did not deplete limited oak deadwood resources), and it is impossible to determine motivations behind their choice. Certainly choosing pine over other easy-to-gather fuels suggests a familiarity with its burning properties, and is visible at Cueva del Camino. Unexpected selection *against* oak in Abric Romani and Bolomor Cave may result from depleting limited oak deadwood stocks. However, Neanderthals at certain sites foraged expediently, or with little knowledge of fuelwood properties, as evidenced by ignoring optimal fuelwoods and foraging for wider ranges of generally-ignored genera. This is evident in Cueva del Conde Level N20A (contrasting with the apparently better-optimised Level 10), Les Canalettes and Riparo Bombrini. Modern people often understand fuelwood properties, and popular fuels are found to rank highly on experimental Fuel Value Indices (e.g. Chettri and Sharma 2007, Dadile and Sotannde 2020, Miah and Islam 2020, Ojelel et al. 2015, Ramos et al. 2008). These scientific traits are therefore evident in wood and visible in burning properties; Neanderthals could theoretically have likewise understood these traits, if they had prior experience.

Other Neanderthals selected high-quality harder-to-gather fuels; this is most notable with low-deadwood fuels which either burn brightly (*Betula*) or are slow-burning (*Juniperus, Olea*). Juniper dominates three site assemblages, and birch forms a large proportion (31%) of the Llonin anthracological assemblage, suggesting that here, extra foraging was worthwhile given improved fire properties. The reverse, where easy-to-gather, low-quality fuels are preferred is seen most notably in El Esquilleu Level IX-XIII where *Sorbus* dominates, and Cueva del Conde where it is extremely common, and Scladina where *Populus* is more common than expected. This suggests that these sites prioritized ease-of-gathering with foreknowledge of different deadwood drop rates and ease of carrying; the exception possibly being Cueva del Conde, where from the vast variety of genera burnt, the selection appears to be random. The very worst fuelwoods, being both low-quality and difficult to gather, are seldom burnt, with the exception of Kaldar and La Vina, where *Salix* was reasonably frequently burnt. This research has highlighted the variety of choices of fuelwood that Neanderthals developed, from those in Llonin burning high-quality fuels at the expense of higher (initial) gathering costs (but overall saving labour due to utilizing slower-burning fuels), through the Cueva del Camino Neanderthals choosing high-quality pine over other easy-to-gather fuels, through the El Esquilleu group prioritizing easy-to-gather fuels at the expense of quality, and finally the Cueva del Conde Neanderthals apparently selecting entirely randomly. The final concluding chapter discusses the implications of this research, synthesizing the knowledge attained thus far and the role of Neanderthal fire in wider Neanderthal studies for the future.

Chapter Eleven: Conclusion.

This thesis has analysed Middle Palaeolithic anthracological records, picking patterns out of data and turning numbers into reconstructions of past behaviours, for an extinct hominin species with which we can in no way communicate. Through assessing their behaviours, I have reconstructed Neanderthal thought processes, lifeways and daily choices. Through analysing small but important parts of daily life, I have inferred information about their more general technological capabilities, as fuelwood foraging techniques translate into hunting strategies, lithic procurement models and more. My three initial research questions from my Introduction have been amply answered; Neanderthals *did* use fire commonly as a species; *occasionally* they facilitated other technologies from this but this was by no means universal; they selected fuelwoods rather than choosing at random, selecting for both fuelwood qualities and ease of gathering; and these apparent selection processes remain when charcoal and pollen biases are considered. Each research question is covered in full detail below, as well as my research's further implications. The idea that Neanderthals were similar to AMH is gaining further traction; we see this through individual technological know-how, similar lifestyles, and particularly regular fire use, creating evening social spaces instantly recognisable from our own lives.

I: *What evidence is there that H. neanderthalensis used fire commonly as a species, and particularly used it to facilitate other technologies (advanced fire use).*

My analysis in Chapter Three has demonstrated the widespread nature of Neanderthal fire, being present in over 80% of sites analysed. This of course is a lower estimate, given natural archaeological loss. This analysis did not account for inter-layer frequency to estimate fire-use frequency within individual Neanderthal lifetimes. This would have been impossible, not only due to inter-site taphonomic differences making standardisation impossible, but also from intra-layer differences within the same site, and multitudes of unknown variables as to how fire use translates to archaeological features. Would hearths being constantly reused in one spot produce stronger (anthracological) signatures, or would previous iterations be cleaned away and destroyed, with only final fire iterations remaining? Palaeolithic palimpsests, and the lack of varved sediment sites where even annual records can be kept, makes this impossible. Furthermore, this analysis only captures home-base fires; what of hunting ground hearths, ephemeral temporary camp hearths, or anthropogenically-caused landscape fires? From the quantity of controlled fire seen, average Neanderthals almost certainly encountered fire regularly throughout their life; whether one created each day, one kept burning throughout an occupation period, odd fires curated from wildfires or lightning strikes, or fires used exclusively for rare lithic heat-treatment events, is unclear from this analysis.

Some Neanderthals must have used fire so rarely as to have made little practical difference to their lives. This is suggested by almost 20% of sites (45 sites) studied in Chapter Three being *completely* fireless (although microscopic research would be needed to fully confirm this in some), and more fully confirmed by detailed inter-level research in Roc de Marsal and Pech de l'Aze IV (Aldeais et al. 2012, Goldberg et al. 2012, Sandgathe et al. 2011). Fire use then was common to *H. neanderthalensis* as a species, but many groups lived without it, either permanently or seasonally. Modern humans may be the same; McCauley's et al.'s 2020 study found that four ethnographic groups, the Onges, Yuqui, Siriono and Northern Ache peoples, could not manufacture fire and relied on pre-existing fire. There would certainly have been Upper Palaeolithic human groups likewise relying on natural fire, which was not always present. Of course, issues of increased loss from older archaeological sites also affects older AMH sites. Murphree and Aldeais (2022) found limited fire use in the Early Upper Palaeolithic, compared with significantly more widespread use in the Gravettian. Whilst this may be due to emerging technologies and increased sophistication, this may also represent some differential loss over time. This may also of course have affected the oldest Neanderthal sites (see Chapter Three, p.100).

Sandgathe and Dibble (2011, 2017) studied two Neanderthal groups, and their conclusions that "Neanderthals were not obligate fire users" (Dibble et al. 2017) have been substantiated by my research; Pech de l'Aze and Roc de Marsal are not two sites with unusually primitive Neanderthals or unusually poor preservation, but are part of wider patterns of some levels/sites being apparently fireless, although further microscopic studies may refute this pattern. Many apparently "fireless" sites might produce fire evidence under more intense scrutiny. However, Dibble's subsequent inference that "the presence or absence of such fires was due to the inability [of Neanderthals] to start fires" (Ibid) cannot be substantiated at a pan-

European level, despite compelling new research by Abdolahzadeh et al. (2022) supporting their hypothesis for that particular site. Warm-climate Neanderthals may have used more fire than cold-climate ones; however, deadwood availability in forests declines in lower temperatures and therefore higher latitudes (Garbarino et al. 2015, Stokland et al. 2016, although see Augustynczik et al. 2024 for a counterview). This may be a more important climatic-dependent factor than lightning strikes. For 80% of sites to show some fire use, Neanderthals must have supplemented natural with anthropogenically-created fire, especially in sites such as Abric Romani where fire was a constant tool.

Regarding advanced fire uses, I have demonstrated the high likelihood of Neanderthal cooking from several proxy sources (modified starch, burnt bone) but also the impossibility of definitively proving it. Cooked food would have been extremely valuable for energetically-challenged Neanderthals in cold climates, and cooking is a simple visual skill that despite requiring time input, comes with few practical risks (aside from carcinogens or burning). Likewise, birchbark or tar hafting adhesive preparation is evidenced at few sites, and lithic heat-treatment at even fewer. It appears that, when these skills were discovered, they became widespread in the community and are well-evidenced at each site. However, for whatever reason, unlike in *H. sapiens*, these skills did not subsequently spread and become species-wide (or at least used by all fire-using groups). This could be because Neanderthal groups, however innovative, periodically went extinct in northern latitudes, being later replaced by other warm-climate Neanderthal groups who could not copy their predecessor's technologies. This may explain technological paucity in northern climates, but why are such technologies uncommon in Iberia (especially Gibraltar), Italy, Greece and Israel, areas of glacial refugia? Neanderthal's short lifespans could have meant that no elderly individuals existed to transmit cultural information (the Grandmother Hypothesis). Exogenous mating practices could have spread pyrotechnic culture, but Neanderthal groups could have been small, inbreeding but seldom encountering others (Vaesen et al. 2019) which limited this cultural spread. Consequently, individual innovative Neanderthals may have spread advanced fire technologies *within* their own groups, which continued until that group became extinct, but did not spread it to others. This may explain the limited clusterings of heated lithics noted in Iberia in Chapter Three (p.96). The fact that these technologies are limited, but that fire use itself is generally widespread, suggests that fire itself, irrespective of its technological possibilities, was sufficiently simple and valuable to Neanderthals for many groups to use it.

II: *Did Neanderthals select specific fuelwoods for their combustion properties, or did they choose indiscriminately according to the Principle of Least Effort?*

Chapter Five has shown that specific selection is visible within Neanderthal sites, through comparing fuel remains with what was available at the time. Furthermore, these selection patterns, when analysed across many sites, show distinctive trends. Pine is dominant (over 50% of the assemblage) in 47% of studied layers, and is overwhelmingly dominant (over 80% of the assemblage) in 29% of cases. Other dominant fuelwoods include larch/spruce, juniper, cherry, olive, almond and maple, with 71% of layers having one obviously-preferred fuelwood type. Tested Iberian sites show obvious choice compared to random environmental availability, and if extended to the other sites, although without definitive evidence of choice, the same few fuelwood trees are consistently exploited across the Neanderthal range, with expected climatic-driven variations (more southerly sites increasingly exploit *Juniperus, Olea* and *Amygdalus*). This prevalence of particular fuels in most sites suggests distinct Neanderthal preferences; either rational or irrational, based on pyrotechnic experience or unsubstantiated group norms and whims. However certain groups, especially those exploiting wider ranges of fuelwoods, selected more randomly, as at Cueva del Conde. This "random" selection could however serve a function, as in this site, "the mixture of ignition species (scrub), of fast combustion (pine) and slower with high calorific value (birch) would be intended to improve the quality and duration of the flame in order to improve the condition of the cave habitat" (Uzquiano et al. 2008, p.130). It is impossible to tell whether diversity or monospecificity is better-adapted, but each probably represents conscious choices by fire-users.

However, whether these fuelwoods were consciously chosen for combustion properties is more debateable. Neanderthal groups better-acquainted with fire *could* choose high-quality fuelwoods, but their foraging experiences would also have taught them the easiest fuelwoods to gather, those dropping abundant deadwood or easily-bundlable for greater loads carried at less effort. Provided such easy-to-gather woods were not actively hard-to-burn fuels, as certain trees such as alder are, they could have been chosen for burning or gathering qualities. The most commonly-burnt fuelwoods, oak and pine, were both easy to gather **and** burnt well – traits which Neanderthals must have recognised, as other trees were easily-harvestable but harder-to-burn, or were harder-to-gather fuels with many positive burning qualities. Chapters Nine and Ten have examined this question, and concluded that there is great variety among different groups regarding this choice. All groups not focusing on oak and pine however appear to attempt to minimise foraging effort, following three distinct models:

1) Some groups intimately understood fuelwood burning properties, and valued slow-burning woods. Each branch burnt for longer, less overall wood was needed per evening and hence fewer foraging trips, even if each foraging trip lasted longer searching for specific trees. Slow-burning woods like juniper, olive and box were therefore selected, in Abric del Pastor, Cova 120, Cueva Anton and Theopetra.
2) Some groups instead understood that certain woods were more easily forageable than others. This was not directly tied to distance from caves, although this would have been a factor, but instead depended on deadwood drop rates, and branch breakability, and/or portability. Dead trees and those with long, straight branches would have been specifically targeted. Pine falls under this category but is also an optimal fuel; sub-optimal, easily-harvestable fuels include larch and whitebeam, found in large quantities in Bojnice III, De Nadale, El Esquilleu, Cueva del Conde, Grotta di Fumane and Pod Hradem.
3) Some groups did not understand either wood combustion properties, or which trees produced abundant deadwood, only gathering wood to satisfy immediate needs, and as close to the cave as possible. Whilst this may seem efficient, many collected woods may have incompletely burnt, requiring more fuel overall, masked by apparent short collection times. Small search radii would have been quickly depleted over time, leading to increasing diminishing returns. Whilst diminishing returns plagued all three models, this one would have been the most susceptible, given that distance was the only factor considered.

Whilst all the models minimise effort, as in time spent foraging, only the third model follows Shackleton and Prins' Principle of Least Effort by having anthracological records represent background environments in decreasing proportions by distance from the cave. This third model is also the only one where Neanderthals could possibly be ignorant of fire use, on at least a semi-regular basis. In the first model, they would have observed different fuelwood combustion patterns before selecting the most energy-efficient ones. In the second, all fuelwood trees could be observed in the landscape during generalised foraging, and their deadwood drop rate and portability noted for fuel alone, as wood serves little other function aside from spear or axe hafting. Furthermore, dense, tough woods which would have been valuable for hafting would have been difficult to cut and collect, and fuelwood would in fact represent the opposite type of wood; dry, dead and preferably rotten and easily breakable. Neanderthals frequently burning rotten wood (Chrzazvez 2006, Thery-Parisot and Texier 2006, Vidal-Matutano et al. 2017) may represent an active choice for their smoking properties, or for ease of gathering.

A possible objection to all these models that each associated anthracological signature could have been produced by chance. If optimal fuels like oak and pine, or deadwood, or slow-burning woods occurred right next to sites, Neanderthals would have just selected those through conserving distance on each foraging trip, irrespective of their combustion properties or ease of gathering. However, two factors argue against this. Firstly, it would be unlikely that selection processes evident in Iberian sites only occurred there, given that preferred Iberian fuels were also preferred elsewhere. Whilst open-air Neanderthal sites *could* have been deliberately situated close to preferred fuelwood resources, and the Principle of Least Effort would apply, cave sites are instead determined by geological and hydrological morphologies along river valleys, irrespective of nearby tree types. Secondly, limited varieties of fuelwoods in Neanderthal fires, often from five or fewer genera, must be far less than that available in the landscape. In sites where pollen and charcoal were compared, there were always more genera available in the landscape than were chosen:

Table 11.1: Comparing the number of fuelwood genera with the availability in nine Neanderthal sites.

Site	**Number of Genera used as Fuel**	**Number of Fuelwood Genera available in the landscape**
El Esquilleu	3	8
Cova de Coll Verdaguer	3	9
Cueva del Camino	2	5
Gorham’s Cave	4	22
Abric Romani	7	9
Bolomor Cave	2	21
Cueva Anton	6	8
Riparo Bombrini	5	20
Teixoneres Cave	2	8

Proportion of available fuelwood types being used ranges from 10% to 78%, with 38% of available fuelwoods utilised on average. By contrast, a modern human study used 80% of available fuelwood species (Specht et al. 2015), and respondents in another study burnt thirty-six different genera as fuelwood (Tabuti et al. 2003). This would suggest that Neanderthals were at least as selective as modern humans in their fuel procurement, if not more so. However in another ethnographic study, out of 114 species burned, only 14% were arboreal charcoal-producing trees (Thomas et al. 2011). This suggests that Neanderthals may also have burnt many shrubby fuels that did not survive as charcoal. However, Neanderthals still exert strong selective effects even among arboreal pools. This preference for Neanderthals using limited fuelwood types extends throughout Europe. Even where complementary pollen data is not available, 13 layers, 21% of those studied, contained three or fewer fuelwood genera. There is extremely little chance that this represents all the trees available in the landscape, implying distinct selection practices. In sites with compared anthracology and palynology, on average 3.8 genera were burnt out of an available 12.2 fuel genera on average; the average number of genera burnt in any other site was 5.2. This is higher than the Iberian average, potentially suggesting different foraging practices, but still well below the number of genera predicted to be available for each site, if similar taxonomic diversities prevailed across Europe. If Neanderthals only utilised c.43% of their available fuelwood resources, they must have been selective.

This therefore strongly suggests that many Neanderthal groups, although by no means all, selected their fuelwood, according to various criteria. The vast majority chose the two genera *Pinus* and *Quercus*, which were both easy-to-collect and high-ranking fuels. Some groups selected for slow-burning woods to reduce daily foraging burdens. Most selected for trees dropping abundant deadwood which was straight and easily portable, and some appeared wholly unselective, possibly resulting from inexperience with fire. Whether all Neanderthals *knew* the motivations behind their choices is unclear, and highly dependent on individual understandings and presence or absence of language. Arbitrary group norms probably defined individual selection processes; one wood was proper to burn and another was improper, a very human trait indeed!

III: *Do these patterns of fuel use and specific choice of optimum fuels stand up to critique when the confusing effects of differential charcoal and pollen production by fuelwood genera are taken into account?*

My conclusions depend on anthracological records accurately representing Neanderthal fuel usage, rather than being artefacts of production or preservation bias. My experiments indicate that these biases, although potentially problematic, were not the main shapers of the Neanderthal charcoal record. I had previously inferred selectivity based on discrepancies between pollen and charcoal records; if recalibration for these biases reduced this discrepancy to near zero, then these discrepancies would be caused by differential charcoal production rather than anthropogenic choice. It was also important to see whether recalibration changed which fuels were dominant when complementary pollen records were unavailable. I tested pollen production, charcoal production, and charcoal fragmentation as three potential areas of genera-specific bias.

Pollen production and dispersal is high variable, as pollen counts vary wildly from season to season and year to year, depending on prevailing wind direction and insect presence. I used published information on differential pollen production; however studies of differential pollen spread and degradation are incomplete, and the thesis' scope did not permit digressing into so novel a field. Analysing Iberian sites demonstrated that applying pollen-production recalibration actually *increased* discrepancies (from an average of 37.92 to 48.67% difference between charcoal and pollen), suggesting instead that differential pollen production partially masks higher discrepancies and greater fuel selectivity. This is partially because favoured fuelwoods, such as oak, birch and pine, produce relatively large quantities of pollen – when recalibrated, their actual landscape presence is less than initially thought, and thus given proportions of fuelwood (inferred from charcoal) must have been more sought-after. The other twenty-four sites lack corresponding pollen diagrams, meaning that discrepancies cannot be analysed; however, it is likely that when they are discovered, selection towards fuelwoods with high pollen outputs like *Betula, Pinus* and *Quercus* will be masked by this bias, and recalibration will be important for understanding the original proportions. This recalibration is likewise crucial to understanding palynological diagrams throughout archaeology, especially given that *Pinus,* a high pollen producer, dominates many Palaeolithic records.

Charcoal production was found to be an important bias, varying from 22.8-42.3% wood-to-charcoal conversion rate at 350°C, and from 0.3-11.3% at 700°C. When compared to *Pinus*, the most common Palaeolithic genus, fuelwoods created between 0.6x and 1.2x the amount of charcoal (between 0.6x and 19.5x at 700°C!). This correlated with six similar but smaller-scale studies, with varying methodologies (precise burning temperatures) causing any differences between their and my results. These varying conversion rates surprisingly did not correlate with density, ash content or calorific value as expected, but correlated well with charring rate (faster-charring woods create less charcoal) and this could be used as a proxy for wood-to-charcoal conversion rate (at 350°C). Different fuelwoods consistently create provably-different wood-to-charcoal conversion rates, which helps understand all anthracological diagrams throughout history, as well as modern charcoal industries.

When production bias was considered with the Iberian sites, charcoal-pollen discrepancies between pollen and charcoal records remained near-identical at 350°C. Although not wholly free from taphonomic bias, as mean increases (2.84%) were less than mean decreases (11.89%), it did not cause it exclusively. Selections towards or against individual important fuelwood genera remained near-identical, with very mild decreased selection towards pine countered by increased selection of oak. 700°C recalibrations produced far more startling results, but quantities of charcoal produced at 700°C are negligible compared to those produced at 350°C (see Chapter Seven, p.177), only minorly contributing towards surviving anthracological assemblages. Production bias minimally affects how we see Neanderthal fuel selection. Looking at all Neanderthal fires, juniper became c.10% less common; pine minimally changing, but both oak and birch becoming more common. These results further suggest that Neanderthals often selected fuels with burning qualities which performed well in everyday fires (long burning duration, minimal smoke and high light and heat outputs), and that this effect is not only produced by differential charcoal production.

My charcoal *fragmentation* experiments showed that, here too, bias is possible, especially given that all anthracological research is determined by number of fragments for each genus, which naturally varies with different fragmentation rates. Crushing one piece of charcoal created between 352 and 963 smaller fragments, with up to 58.73% of the charcoal being under 1mm and thus unidentifiable through standard morphological characteristics. Larger initial masses of charcoal naturally created, on average, larger but fewer fragments (when standardised to a standard 1g input mass); which on the one hand could under-represent genera with fewer overall fragments, but also over-represent it if each fragment is more easily identified to the correct genus. There is minimal correlation between wood density and fragmentation rate; however *charcoal density*, (which again varies from wood density in genera-specific fashions) does correlate, with higher-density charcoals creating fewer, larger fragments. Charcoal density could therefore act as a proxy here. When the number of identifiable fragments was compared to *Pinus*, *Quercus* fragmented into only half as many pieces under the same pressures.

When fragmentation-bias recalibration was undertaken, juniper's usage decreased by 22%, suggesting that fragmentation-bias may have affected the apparent usage of this genus. The use of pine decreased by 12%; however usage of *Salix/Populus* increased by 24%, that of *Betula* by 46%, and that of *Quercus* by 96%! This suggests that of all potential factors, fragmentation bias is potentially the most important in confusing anthracological records. Regarding Neanderthal selection however, this change was not large enough to suggest that fragmentation *caused* the charcoal-pollen discrepancies as, following recalibration for Cova de Coll Verdaguer and Abric Romani, average discrepancies increased slightly from 16.4 to 17.3, with only one layer increasing and one layer decreasing its discrepancy, and the rest remaining identical. In terms of *selection*, pine may have been slightly less selected-towards, and cherry more so, but by no means so as to make the latter a preferred fuel. In terms of fuelwood *prevalence* in all sites (Table 11.2 below), although *Pinus* decreases by over 10% through combined production and fragmentation bias recalibrations, *Quercus* increases; the proportion of these two favoured fuels combined decreases marginally from 52.63% to 49.62%.

Table 11.2: The overall presence of various genera throughout all Neanderthal fires, recalibrated for 350°C burning and fragmentation biases.

Genus	Proportion within all Neanderthal fires (over 1% presence)	Proportion within all Neanderthal fires, recalibrated for 350°C burning (over 1% presence)	Proportion within all Neanderthal fires, recalibrated for 350°C burning and fragmentation bias (over 1% presence)
Other	3.78	4.00	3.91
Sorbus	1.10	1.18	0.89
Fraxinus	1.27	1.49	1.51
Buxus	1.35	1.34	1.98
Betula	1.50	1.89	1.74
Carpinus	1.71	2.05	3.62
Larix	3.42	2.77	2.48
Picea	3.44	3.22	2.90
Olea	3.95	4.92	5.13
Acer	4.58	5.27	5.49
Amygdalus	5.21	5.61	5.56
Prunus	7.28	7.01	7.60
Juniperus	8.78	7.93	7.58
Quercus	10.19	11.86	17.91
Pinus	42.44	39.46	31.71

Although fragmentation bias may be responsible for the precise proportions of each fuelwood genus, Neanderthals still had two obviously-preferred fuelwood genera, oak and pine; juniper and *Prunus*-type trees were popular alternatives in Mediterranean-type climates, and other trees were gathered in smaller quantities; presumably following optimisation of foraging processes. This analysis has showed that fragmentation bias is the biggest cause of potential confusion in the charcoal record. Methodological changes from fragment counting to volumetric or mass measurements would greatly alleviate this bias however, and I call upon future anthracological papers to consider this as an alternative research method.

My original patterns remain but are better-defined following these analyses. Apparent increased selectivity towards *Pinus* (+12% through pollen recalibration), is offset by a -10.7% charcoal presence. Oak becomes minorly more selected for both in pollen (+2.2%) and charcoal (+7.7%). The initial selection against *Quercus* had been unexpected, given its ubiquity elsewhere in prehistory and its generally favourable reception as a fuelwood. Its deadwood reserves are limited, but it is unlikely that small, highly mobile Neanderthal populations would have exhausted this resource. Increased oak burning implied by recalibration puts Neanderthal fires more in line with other AMH fires also exploiting oak as a core fuel (e.g. Ramos 2005, Rubiales et al. 2011). Juniper's decreased positive selection (-6.8%) and decreased charcoal presence (-1.2%) both suggest that juniper fuelwood was marginally less popular than initially thought; however in sites where it dominated, this dominance still remains. Fine-scale analysis such as this is impossible without taking these myriad factors into account. Further factors, such as differential pollen spread and degradation, and charcoal identification rates, may also show genera-specific differences which may, when mapped onto these and other datasets reveal important hitherto-obscured patterns.

IV: Technological and Archaeological Implications.

If Neanderthals were more complex in fuel procurement than once thought, this in turn affects their other technologies, in contrast with *H. sapiens*. Neanderthal fire development, and particularly complex fire-associated technologies like lithic heat-treatment, may have been hindered by group isolation. This thesis has demonstrated that particular individual Neanderthal sites display forward-planning technologies (see Introduction, p.21); selection of distant lithic types (Gomez-Olivencia et al. 2018) including obsidian (Doronicheva), distant bitumen for hafting at Umm el Tlel (Boeda et al. 2008a,b), prey specificity at many sites including Ortvale and Klde and Riparo Tagliente (Adler et al. 2006, Vettese et al. 2021), and lithic caching in sites including Kabazi V and Mount Pua (Barkai and Gopher 2011, Veselsky 2008). However, no Neanderthal sites show all these behaviours in the way that contemporary AMH sites did. The key difference between Neanderthals and AMH is that, in the latter, innovations spread group-to-group to form pan-European "cultures" in the Upper Palaeolithic, with ritual and subsistence practices. However, isolated Neanderthal groups repeatedly died out, losing technological gains and preventing this spread which otherwise may have ensured their survival. Neanderthal groups would have been much more individual, tailored to local subsistence regimes.

Nonetheless, individual group complexities certainly indicates that Neanderthals could act similarly to contemporary AMH, and only were hindered by a lack of learning opportunities. *Advanced* fire uses (cooking, lithic heat treatment and melting hafting materials) were acquired by odd groups and subsequently lost, due to their how few sites they appear in, and yet how prevalent they are in those sites in which they are found. Many more Neanderthals selected specific fuels, evidencing forward-planning and knowledge of optimum fuelwoods for desired purposes. This is in keeping with other forward planning activities; selecting raw lithics has continued since the Oldowan (Delagnes et al. 2023, Sherwood 2021). The fact that many Neanderthals, even without the skills for most advanced technologies involving fire, still selected optimum woods, implies that selectivity is extremely innate to ‘human’ nature. Although selectivity is evidenced in lithics since *Homo erectus*, Neanderthals are the first to properly select optimum prey for hunting; and now, this study has further demonstrated another ‘first’ aspect of selectivity, in fuelwood choices. Innate selectivity may not be a cognitively-modern trait, but when hominins apply it to successively more parts of their lives, they become more and more like us. The lithic optimisation of *H. erectus* was the first step towards modern technological behaviours; Neanderthals massively expanded this selective repertoire.

Fire use *as a whole* appears in 80% of sites. As yet, no comparable study for Palaeolithic modern humans exists (except Murphree and Aldeais 2022 – see pages 65 and 311 in this thesis); however as modern humans are evolutionary-obligate fire users, few *H. sapiens* sites would be fireless. My study implies that most Neanderthals could conceptualise and use fire; a further subset could possibly conceptualise it, but could not use it, lacking fuelwood or knowledge of how to create fire at will. This implies that fire use was much more innate to *H. neanderthalensis* than once thought, at least conceptually, and possibly, by proxy, to *H. erectus*, if both successor species to it could intrinsically understand it. The findings that many Neanderthals also *optimised* fire events, either improving burning properties or minimising foraging efforts, further suggests daily familiarity with fire. I initially assumed that optimising burning events (e.g. higher temperatures, lack/presence of smoke, light output) was linked to specific technologies. However, Neanderthals appear to have optimised their fires regardless of this, mixing fast-burning pine and slow-burning oak and juniper. Whilst Neanderthals did not always use their fires for more than mere warmth and light, its quality was important to them even without the presence of more demanding fire-related tasks.

Furthermore, their fire mirrored other aspects of their lives, both in terms of optimisation and forward-planning. Inexperienced Neanderthals expediently gathering fuel to monopolise natural fire only occurs in a few sites. As with forward-planning and coordinated hunting enabling targeting of larger prey and more time-effective and safer hunting, placing sites near high-quality lithic sources reduces foraging times, and caching practices allows storage for returns to seasonal sites. Fuel selection likewise reduced time spent on this technology (outside burning times). Fuelwood-gathering is costly; optimisation in turn allowed wood gathering to occur *alongside* other foraging activities during daily subsistence hours. Likewise, waking and refuelling fires at night is also potentially costly; optimising for slow-burning woods reduced these costs. Both reduced the fire costs to only time spent igniting and building hearths, and risks of being burnt; costs also minimised by selecting dry non-sparking woods. Neanderthals using fire rarely and foraging randomly would have found it costly, despite the benefits. When it became inherent and part of practiced daily routines, fire use cost little more than being restrained to home bases at certain times; which itself came with benefits of Sight, Security and Socialisation.

V: Further Research.

As mentioned, further research into pollen spread and degradation mechanisms could elucidate potential palynological biases. Recent vegetation-pollen comparison studies demonstrate taphonomic bias (Lawing et al. 2021, Val-Peon et al. 2023). Studying inter-genera (and inter-species) sporopollenin differences would demonstrate resistances to degradation (Gabarayeva et al. 2003, Jardine et al. 2021, McGarry and Caseldine 2004, Mujtaba et al. 2018, Wang and Dobritsa 2021). Oxidising tests such as those by Lebreton et al. (2010) could be expanded on to create predicted degradation rates by exine thickness (and thus by genus). Understanding how different pollens react to common chemical preparation treatments (e.g. sodium hexametaphosphate or Lycopodium tablets), as well as mechanical resistance to centrifuging, would help ascertain if modern treatment methods cause further biases. More pollen reference collections would also assist in enabling rarer genera, such as *Celtis,* to be as consistently identified as *Pinus.*

Further anthracological research could better examine genera-specific charcoal production in real-life experimental fires, and how this differs from laboratory methods. Certainly, proportions created at any temperature will be less than in optimal oxygen-excluding furnaces. If more laboratory studies are undertaken, understanding genera-specific conversion rates at more temperatures, in increments of 50°C from 350°C to 700°C, would be highly beneficial. *Pinus* was in the top 17% highest charcoal-producing genera at 350°C, but in the lowest 7% at

700°C; *Larix* in the top 4% at 350°C and the bottom 27% at 700°C; *Celtis* in the bottom 35% at 350°C, but in the top 2% at 700°C. Research could determine how these proportions change with temperature; at which temperature fires produced most charcoal, and how real-life conversion rates differ from laboratory experiments. Real-life fires, on the model of Hoare (2020) and following identical procedures, could also determine maximum temperatures, burning durations and lux outputs of a wider range of genera and to determine their value to Neanderthals. The current omission of *Juniperus, Prunus, Amygdalus* and *Acer* (four of the six most common genera in the Middle Palaeolithic anthracological record) from temperature, burning duration and light output experiments is regrettable, and their inclusions would be most valuable. My recalibration tables likewise have much wider applications than the Middle Palaeolithic record; they can address **any** anthracological bias throughout archaeology, and enable more accurate understandings of local palaeoenvironments.

As excavations progress, I hope that more sites with hearth features will publish detailed anthracological and palynological diagrams to enable further dialogue. Currently, fewer than 25% of sites with charcoal (29 out of 128) have proper published anthracological diagrams; pollen could theoretically be analysed from many of them. Further excavation can hopefully also reveal more undisturbed sites where *individual* hearth features can be analysed. This has been possible in El Salt, with H44, H53b and H57 (Vidal-Matutano 2017), but is currently uncommon; at best, layers are subdivided into Archaeosedimentary Facies Associations (AFAs). Individual hearth assemblages can crucially reveal how individual fires operated; in El Salt, H44 and H53b are overwhelmingly dominant with *Pinus* fuels, with minor *Acer* input; in H57 however, *Pinus* and *Acer* proportions were equal, along with many burnt *Acer* seeds (Ibid). Perhaps H57 represents a specialist maple-seed roasting hearth, or perhaps the seeds were still attached to burning branches; this fire would have lasted longer and emitted less heat than the pine-dominant ones however. These distinctions, especially between temporally-contiguous hearths, provide valuable insights into individual decision-making. New excavations and research can also reveal finer-scale environmental data, in particular continuing Sandgathe and Dibble’s work of correlating fire with environmental conditions to determine how constraining climatic conditions were to fire use. Further excavation will also allow finer chronological resolution, to better tie local reconstructed biomes to wider climatic changes.

Further research into the intentionality of heated lithics and burnt bone will reveal the real spread of Neanderthal advanced pyrotechnic-dependent technologies. In particular, ESR testing combined with a lack of visual heating damage could detect heat-treated lithics, and Differential Scanning Calorimetry combined with an increased presence of cyanamide could detect carefully-cooked bone. Information on the intentionality of both these metrics is crucial to determine the level of these two technologies throughout the Neanderthal world. Analysing previously-untested Neanderthal tools would also help determine how many finished tools had been heat-treated. Understanding the intentionality of heat-treated lithics and burnt bone would help solve the conundrum mentioned in Chapter Three, whereby intentional heat-treatment at only open-air sites would suggest that there was more fire in caves than open-air sites; if few lithics were intentionally heated, this instead suggests equal fire in both site types but preferential cooking in caves, which analysing bone attributes could reveal.

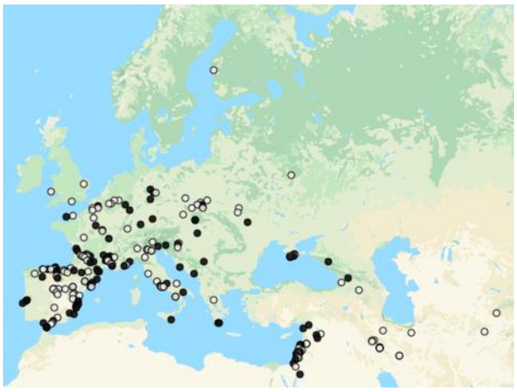
VI: Concluding Thoughts.

The Middle Palaeolithic record is highly incomplete, and future excavations of additional sites and layers will no doubt shed further insight into the nature of Neanderthal fire use. Despite criticisms, it is always easier to prove presence than absence; those arguing for Neanderthal burial need only find one perfect, undisputable example one day. The discovery of a perfectly-preserved Neanderthal hearth with evidence of prior preparation, lithic heat treatment and undisputable cooking would of course prove that Neanderthals *could* do all of these things. However, this thesis has been less about individual exceptional finds, but more about synthesising data over very long spatial and temporal scales, to analyse trends and understand Neanderthals at a species level. Although the key concept of *fuelwood selection* may change, if many more sites publish palynological data, and comparison with the anthracology shows no selective trends, I do not believe that this will be the case. The wider trends of Neanderthal fuel choice across Europe will remain until many more sites have been excavated. The evident human-like choices made by *H. neanderthalensis* have only been strengthened rather than weakened by further discoveries and finer-grained data in the past decade, and fire use is no exception. To a Neanderthal, what I have deduced would not be important, as such behaviours would have been so ingrained into many of their daily lives as to be routine and to have no novelty. However, it is only from an unbiased analysis of these routine activities that we can truly build up an accurate picture of *Homo neanderthalensis* technological progress.

Appendices.

I: Appendix One.

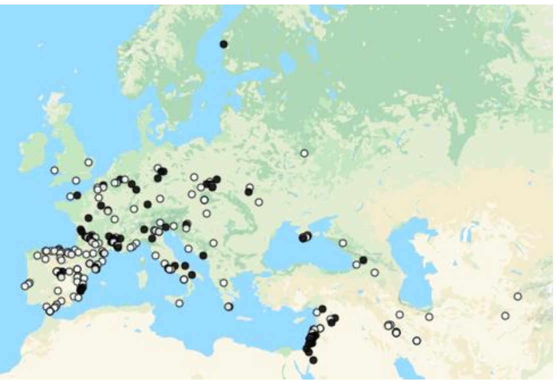
Map A1: Middle Palaeolithic open-air sites correlated with the number of fire proxies (charcoal, ash, burnt sediment, burnt lithics, burnt bone) in them; 0 proxies (white), 1 proxy (green), 2 proxies (blue), 3 proxies (pink), 4 proxies (red), 5 proxies (black).



Map A2: All Middle Palaeolithic sites, either with burnt bone present (black) or without it (white).

Map A3: Middle Palaeolithic cave sites, either with burnt bone present (black) or without it (white).

Map A4: Middle Palaeolithic open-air sites, either with burnt bone present (black) or without it (white).



Map A5: All Middle Palaeolithic sites, either with burnt lithics present (black) or without it (white).

Map A6: Middle Palaeolithic cave sites, either with burnt lithics present (black) or without it (white).

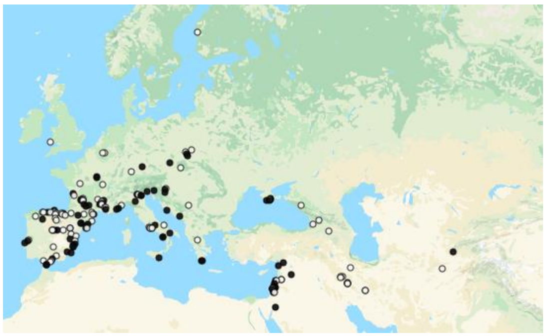
Map A7: Middle Palaeolithic open-air sites, either with burnt lithics present (black) or without it (white).

Map A8: All Middle Palaeolithic sites, either with charcoal (black) or without it (white).

Map A9: Middle Palaeolithic cave sites, either with charcoal (black) or without it (white).

Map A10: Middle Palaeolithic open-air sites, either with charcoal (black) or without it (white).

Map A11: All Middle Palaeolithic sites, either with hearths (black) or without (white).



Map A12: Middle Palaeolithic cave sites, either with hearths (black) or without (white).

II: Appendix Two: Site Descriptions.

Abric del Pastor: This small rockshelter (60m^2) is located in the Mariola Mountains of Alicante (Spain). First excavated in 1953, it has been recently re-excavated since 2005. In a 1.5m deep sequence, six stratigraphic units have been found. The Neanderthals may well have burned dead wood, and a recent investigation has found well-preserved evidence of a single occupation episode, a rare occurrence

References: Sossa-Rios et al. 2022, Vidal-Matutano et al. 2015.

Abric Romani: This well-known cave contains 27 archaeological layers in a 20m-thick section; layers A-K dating from c.40-52ka BP contain the Middle Palaeolithic remains. The hearths vary from those used for short-term cooking and those burning overnight; many have lithic scatters around them. As well as the plethora of hearths, there is also evidence of Neanderthals curating and cleaning their living spaces. The animal bones are mainly from medium to large herbivores, deliberately hunted and showing many green breaks and frequent anthropogenic cutmarks.

References: Gabucio et al. 2018, Vaquero et al. 2001, 2004.

Abri du Maras: This rockshelter is situated 70m above the Ardeche river, composed of three sedimentary layers. The middle of the sequence is U/Th dated from 72-91ka BP. Neanderthals lived here during temperate forested conditions in Layer 5, and abandoned it during the cold phase in Layer 4. There are abundant lithic remains, using the Levallois flaking technology on flint cortical cores.

References: Moncel et al. 2015.

Abrigo de la Quebrada: This rockshelter is located 65km north-west of Valencia, Spain, c.730m above sea level. It faces north-west and is at the bottom of a narrow gorge, often in darkness. The archaeology is over 3m thick, distributed into nine stratigraphic units. There is an extremely high desntiy of occupations, and over 18,000 lithics and 100,000 bones have been found. Radiocarbon dating has dated the Neanderthal occupations from 43-51ka BP.

References: Carrion Marco et al. 2019, Real et al. 2018.

Aguilon P5: This cave is found in the Iberian System mountain range, in the north-east of the peninsula. A large cave, 20m long and 8m wide, it has been excavated since 2010. Four archaeological levels have been revealed, evidencing hearths and multiple occupations. The whole is radiocarbon dated to MIS 3 (34-46ka BP).

References: Mazo and Alcolea 2020.

Bojnice III: This site was excavated from within the moat of Bojnice Castle ('Castle of the Spirits'), Slovakia. 21 geological and 11 archaeological layers are preserved, dating from MIS 5e to MIS 3. The lithics mostly demonstrate the discoid technique, with a large number of bifaces.

References: Valoch and Moncel 2013.

Bolomor Cave: This cave is located near the Spanish coast near Valencia. The cave opened c.500ka ago, and consists of 17 geoarchaeological levels, dated 121-233ka BP. Four Neanderthals have been recovered from here since 1989, alongside scrapers and denticulate tools. There are fifteen hearths present, and the individuals subsisted mostly on hunting young elephants and ungulates.

References: Vidal-Matutano et al. 2019.

Cova del Coll Verdaguer: This karstic cave has a rich faunal and floral assemblage, mostly representing carnivore (hyenid) dens and associated prey. However there is anthropogenic assemblages in scattered charcoal, burnt bone and 14 lithic fragments, dated to 90.4ka BP, which were mostly deposited when complete, although there is some refitting. This site is however generally ephemeral, although dissolutions and concretions suggest that much has been lost.

References: Daura et al. 2017, Sanz and Daura 2018, Villa and Bartram 1996.

Cova Gran: This is a very large rockshelter with an area of over 2500m^2, situated at 385m above sea level in the Eastern PrePyrenees. Since 2004, 40m^2 has been excavated, revealing seven layers. The top three are Early Upper Palaeolithic, and the lower four are Late Middle Palaeolithic. The Middle Palaolithic layers are 1.5m thick, and bedrock has not yet been reached. All are palimpsests, containing all elements of knapping and retouching. There is a large faunal assemblage, including *Stephanorhinus, Bos, Equus, Cervus, Capra* and *Oryctolagus*.

References: Allue et al. 2018.

Cova 120: This is a less-studied cave, approx. 25m deep and 460m above sea level, located in the Eastern Pyrenees. Excavated 1985-1989 and 2003-2006, nine layers have been uncovered, dating from the Middle Palaeolithic to the Bronze Age. The Middle Palaeolithic layers have been dated from MIS 7 to MIS 4. A very large suite of animal remains have been found, mostly accumulated by carnivores. Neanderthal occupation here is evidenced, but limited.

References: Agusti et al. 1991.

Cueva Anton: This rockshelter is located in the River Mula valley, Spain. Excavated since 1991, a 4m thick stratigraphy has been uncovered, dated MIS 4-3 (75-36ka). A Neanderthal camp has been found in various parts of the 600m^2 revealed. The most notable find here is a perforated scallop shell bearing evidence of pigment, a possible example of symbolism and art. Dated to c.43ka BP, it is one of a very limited repertoire of Neanderthal portable art pieces.

References: Zilhao et al. 2016.

Cueva del Camino: Described as “the most complete MIS 5 record from the Iberian peninsula” (Arsuaga et al. 2012, p.55), this cave however is likewise primarily a carnivore den, with its anthropogenic input being from slope erosion uphill resulting in the cave being filled with an exterior deposit. This contains charcoal but no other fire evidence; there are also two Neanderthal teeth and a few lithics, but few cutmarks or anthropogenic fractures on the bones. This site was seldomly occupied then, and represents ephemeral Neanderthal presence.

References: Arsuaga et al. 2010, 2012.

Cueva del Conde: The Cueva del Conde. in the River Trubia Valley, Spain, is best-known for its Aurignacian rock art. However, it also has a strong Middle Palaeolithic signature in the lower layers. Two Mousterian layers have been revealed. Radiocarbon dating on bone and charcoal has dated these levels 37-38ka BP. A very large number of mall mammals and amphibians recovered has allowed a detailed reconstruction of the surrounding biomes and landscape.

References: Lopez-Garcia et al. 2011, Uzquiano et al. 2018.

De Nadale: This karstic cave is found in the Italian pre-Alps. First discovered in 2006, it has been excavated since 2014. Eight stratigraphic units contain one inhabited layer (SU7). SU7 contains a Quina Mousterian assemblage, U/Th dated to 70ka BP, as well as many fragments bones, charcoal and one singular Neanderthal tooth. There are many bone retouchers, used to shape and rejuvenate lithic scrapers; the Neanderthals here mostly hunted *Megaloceros, Cervus, Bos* and *Bison*. The bones were defleshed, and the long bones then fractured for marrow recovery.

References: Jequier et al. 2015, Vidal-Matutano et al. 2020.

El Esquilleu: This cave has a strong MIS 3 presence, dating c.36-51ka BP, with a wide range of hearth, burnt bones interpreted as being used as a deliberate fuel. Prey mortality profiles suggest deliberate hunting specialising in solitary adult ibex and chamois, but low local mobility, mostly staying within 5km of the site (seen through lithic procurement sources). The different lithic assemblages display Discoid, Levallois and Quina reduction sequences respectively, and there is evidence for extensive lithic maintenance and recycling.

References: Cuartero et al. 2015, de los Terreros et al. 2014, Uzquiano 2006, Uzquiano et al. 2010, Yravedra and Uzquiano 2013, Yravedra et al. 2006.

El Salt: El Salt represents one of the best sites in Iberia for Neanderthal fire evidence. Excavated since 1986, the site first came to prominence when six Neanderthal teeth were discovered in 1987. The deposits are 6.3m thick, divided into 13 lithostratigraphic units, which have been TL-dated between 60 and 45ka BP. As well as the extensive fire use, El Salt has provided examples of Neanderthal coprolites, which revealed an omnivorous Neanderthal diet.

References: Rampelli et al. 2021, Vidal-Matutano et al. 2018.

Gorham's Cave: This cave represents one of the final Neanderthal refugia, where they may have survived till as recently as 28ka BP, although this is likely far too young. The cave contains cemented hearths and common fire use; an engraving in the cave may represent a rare example of Neanderthal abstract thought and art, and hunted golden eagles may represent harvesting for their feathers and talons for personal decoration.

References: Finlayson et al. 2008, 2019, Goldberg and MacPhail 2012, Rodriguez-Vidal et al. 2014.

Grotta di Fumane: This is a cave in the Veneto pre-Alps (Italy). Excavated since the 1990s, 11 layers have been excavated, dating from the Late Middle Palaeolithic to the Early Upper Palaeolithic. Mousterian Neanderthals lived in layer A5, dated c.43ka BP. Above this, a transitional Uluzzian technocomplex has been excavated. Grotta di Fumane is well known for intentional removal of feathers from various birds by Neanderthals, perhaps to use as personal decorations.

References: Basile et al. 2014, Peresani et al. 2011.

Kaldar Cave: Excavated since 2014, Kaldar Cave in Iran has produced evidence of both modern human and Neanderthal industries. The modern humans are dated 23-29ka BP, and the Neanderthal occupations from 38-54ka BP (Bazgir et al. 2017). The extensive charcoal assemblage has allowed a reconstruction of a mostly *Prunus*-dominated landscape.

References: Allue et al. 2018.

Klissoura Cave: This is a karstic cave in the northeastern Peloponnese (Greece). Excavated 1989-1990, sediments 5m deep were uncovered, divided into 14 stratigraphic units; six Middle Palaeolithic, seven Upper Palaeolithic and one Mesolithic. Whilst the Middle Palaeolithic layers evidence less intensive activity than the later Upper Palaeolithic ones, they contain hearths and lithics. There is also a unique instance of the transitional Uluzzian industry, the only instance thus far to be found outside Italy.

References: Ntinou 2021, Starkovich 2017.

La Vina Cave: This cave is in the Nalon river basin, Spain, 292m above sea level. A large cave, it is 25m high and 30m deep. Excavated 1980-1996, its long sequence covers the Mousterian, Protoaurignacian, Aurignacian, Gravettian, Solutrean, Magdalenian and later Holocene. In the central sector, no Mousterian remains were found, but they were present in the Sector Occidental.

References: De la Rasilla et al. 2020.

Llonin Cave: This cave site is found in the Cares-Deva River Basin, Spain. This karstic cave was excavated 1987-1997, revealing archaeology from the Mousterian, Gravettian, Solutrean, Badegoulian, Magdalenian and Bronze Age. The upper layers show abundant prehistoric art of numerous prey species.

References: De la Rasilla et al. 2020.

Nesher Ramla: This site is a karstic sinkhole in the Judean Mountains, found by accident when quarrying for cement. The Middle Palaeolithic layers are 8m thick, subdivided into six stratigraphic units. Units III and V have the highest density of lithics. The whole sequence has been OSL dated from 78-160ka BP, and TL dated to 117-185ka BP. The whole site appears to be MIS 5 and 6. The lithics were most reduced using the Levallois method.

References: Allue and Zaidner 2022, Guerin et al. 2017.

Les Canalettes: The rockshelter is at 700m above sea level on the southern border of the Massif Central, France. Excavated in the 1960s, and then again from 1980 to 1997, exposed 30m^2. The site is TL dated to the end of MIS 5a, at 73ka BP. The lithics were made from local sources, and the site was occupied between spring and autumn, based on ungulate tooth eruption. There are few carnivores or carnivore marks, suggesting that Neanderthals were responsible for procuring most of the faunal remains here.

References: Audiard et al. 2021, Valladas and Joron 1993.

Pod Hradem Cave: This cave is located in the northwestern Moravian Karst, in the Czech Republic. A small cave, its entrance is only 3m wide and 1.5m tall, and 14m long, 10m wide and 5-7m high inside. Excavated in the 1890s and 1950s, 90m^2 has been uncovered. Originally defined as a cave bear hibernation den, Neanderthal occupations have been more recently recognised. The whole deposit is radiocarbon dated to 32-48ka BP.

References: Nejman et al. 2018.

Riparo Bombrini: This collapsed rockshelter is located in Liguria, Italy, near the Tyrrhenian Sea. Discovered inn 1887 during the construction of the Genova-Marseilla railway, it was only excavated in 1938, and again in 1976 and 2002-2005. The cave Mousterian and Proto-Aurignacian years spanning in between 35 and 45ka BP. The upper Mousterian levels are scattered, whilst the lower levels retain spatially distinctive hearth features. Most of the Mousterian correlated with a warm climate, although the final Mousterian was distinctly cooler.

References: Arobba and Caramiello 2009.

Scladina Cave: This cave sits on the right bank of the Meuse RIver in Belgium, extending 39m into the bedrock, from 6 to 12m in height. Excavated since 1978, two Middle Palaeolithic units have been found. The upper one, 1A, contains 4500 lithics, deposited by debris flow during the Weichselilian Middle Pleniglacial, dated 37-40ka BP in MIS 3. The lower complex was deposited in MIS 5d to 5b, in the Weichselian Early Glacial Period. In this later, over 12500 faunal remains have been found, including 26 bone retouchers made from cave bear bone.

References: Abrams et al. 2014, Pirson et al. 2008.

Teixoneres Cave: Teixoneres in a karstic cave near Barcelona, Spain at 900m above sea level. Containing galleries 30m long, the cave has been excavated in the 1950s, 1973, and since 2003. The sediment is 6m thick, containing 15 layers, of which I to IV belong to the Late Pleistocene and are U-series dated to 100ka BP, within MIS 5c. Neanderthals concentrated their activities at the cave entrance, which they occupied successively for c.7000 years; the deeper recesses of the cave were consistently used by carnivores, with minimal to no Neanderthal presence. The Neanderthal occupations would have been short-lived but frequent.

References: Lopez-Garcia et al. 2012, Zilio et al. 2021.

Theopetra Cave: This cave is situated on the edge of the Thessaly plain in central Greece. It is the cave in Greece with the longest archaeological record, dating from the Middle Palaeolithic until the Neolithic. The Middle Palaeolithic levels are dated from 57 to 129ka BP. The earliest Neanderthals lived in a Prunus-dominated open park-woodland during MIS 6, followed by temperature woodlands; in late MIS 5, this was replaced with Juniperus-dominated steppe. By the Upper Palaeolithic, temperate woodlands had re-established themselves.

References: Ntinou and Kyparissi-Apostolika 2016, Valladas et al. 2007.

III: Appendix Three: Original Burning Values for Charcoal Conversion Rate Experiments.

Tables A1-A42: Original burning calculations for 42 genera at 350°C.

A1: *Acer* (350°C) – Specimens 4 & 5 excluded from Means						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss**	**Charcoal Mass**	**% Weight Remaining**
1	5.9419	35.8988	31.6369	4.2619	1.68	28.27
2	5.9234	37.7104	33.4123	4.2981	1.6253	27.44
3	6.1039	38.2249	33.6983	4.5266	1.5773	25.84
4	5.7721	36.8973	34.1999	2.6974	3.0747	64.92
5	5.0733	36.2921	33.9572	2.3349	2.7384	53.98
6	6.4271	35.8283	31.0578	4.7705	1.6566	25.78
7	6.8893	38.4612	33.5987	4.8625	2.0268	29.42
8	6.3469	36.4043	31.9824	4.421	1.9259	30.34
9	6.0749	38.448	34.1895	4.2585	1.8164	29.90
10	6.0013	35.1782	30.7693	4.4089	1.5924	26.53
Mean	**6.2136**	**37.0193**	**32.5432**	**4.601**	**1.7376**	**27.94**

A2: *Alnus* (350°C) – Specimens 6 & 8 excluded from Means						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss**	**Charcoal Mass**	**% Weight Remaining**
1	4.0283	33.9609	31.0633	2.8976	1.1307	28.08
2	5.1857	35.9867	33.0231	2.9636	1.2221	29.20
3	5.2478	37.3383	33.4982	3.8401	1.4077	26.82
4	4.394	35.5309	32.2958	3.2351	1.1589	26.37
5	4.9368	36.1474	32.4483	3.6991	1.2377	25.07
6	4.5451	34.0262	31.6356	2.3906	2.1545	47.40
7	4.6789	36.2766	32.8803	3.3963	1.2826	27.41
8	5.1984	35.3731	33.1053	2.2678	2.9306	56.38
9	4.1591	36.4923	33.5648	2.9275	1.2316	29.61
10	4.8459	34.0189	30.4161	3.6028	1.2431	25.65
Mean	**4.6846**	**35.7203**	**32.3987**	**3.3203**	**1.2393**	**27.275**

A3: *Amygdalus* (350°C)						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	6.2027	36.2015	31.7439	4.4576	1.7451	28.13
2	6.4322	38.2184	33.6601	4.5583	1.8739	29.13
3	6.2919	38.3982	34.2338	4.1644	2.1275	33.81
4	5.2849	36.3674	32.5108	3.8566	1.4283	27.03
5	5.7318	36.8984	32.863	4.0354	1.6964	29.6
6	6.1486	35.5721	31.4223	4.1498	1.9988	32.51
7	5.6524	37.0805	33.0844	3.9961	1.6563	29.3
8	5.7996	35.8551	31.6571	4.198	1.6016	27.62
9	6.0181	38.4302	34.3726	4.0576	1.9605	32.58
10	5.6859	34.9287	30.8807	4.048	1.6379	28.81
Mean	**5.9248**	**36.7951**	**32.6429**	**4.1522**	**1.7726**	**29.852**

A4: *Arbutus* (350°C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	5.2317	35.1961	31.3474	3.8487	1.383	26.44
2	5.3086	37.1088	33.2601	3.8487	1.4599	27.5
3	7.7456	39.9285	33.9097	6.0188	1.7268	22.29
4	5.7045	36.7833	32.4152	4.3681	1.3364	23.43
5	6.5196	37.7376	32.681	5.0566	1.463	22.44
6	4.9762	34.3675	30.6762	3.6913	1.2849	25.82
7	6.1718	37.687	33.0398	4.6472	1.5246	24.7
8	5.9379	36.0516	31.5646	4.487	1.4509	24.43
9	5.3282	37.6824	33.6644	4.018	1.3102	24.59
10	5.5855	34.774	30.4214	4.3526	1.2329	22.07
Mean	**5.851**	**36.7317**	**32.298**	**4.4337**	**1.4173**	**24.371**

A5: *Betula* (350°C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	5.274	35.2749	31.3255	3.9494	1.3246	25.12
2	5.5883	37.4421	33.1441	4.298	1.2903	23.09
3	5.4427	37.631	33.4146	4.2164	1.2263	22.53
4	5.7633	36.9522	32.7742	4.178	1.5853	27.51
5	6.1213	37.3333	32.6127	4.7206	1.4007	22.88
6	5.2717	34.6628	30.4908	4.172	1.0997	20.86
7	5.8044	37.3212	32.9102	4.411	1.3934	24.01
8	5.5768	35.6739	31.8353	3.8386	1.7382	31.17
9	5.6486	38.0119	34.2355	3.7764	1.8722	33.14
10	5.8342	35.086	30.6739	4.4121	1.4221	24.38
Mean	**5.6325**	**36.5389**	**32.3417**	**4.1973**	**1.4353**	**25.469**

A6: *Buxus* (350°C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	7.231	37.1766	32.0866	5.09	2.141	29.61
2	6.7565	38.5545	34.1555	4.399	2.3575	34.89
3	8.1565	40.312	35.0035	5.3085	2.848	34.92
4	6.3871	37.4868	33.0621	4.4247	1.9624	30.72
5	7.5099	38.7451	33.493	5.2521	2.2578	30.06
6	6.6144	36.0186	31.4709	4.5477	2.0667	31.25
7	6.5877	38.0708	33.4721	4.5987	1.989	30.19
8	6.5643	36.6646	32.4064	4.2582	2.3061	35.13
9	7.0236	39.4044	34.5693	4.8351	2.1885	31.16
10	6.427	35.6529	31.4864	4.1665	2.2605	35.17
Mean	**6.9258**	**37.8086**	**33.1206**	**4.6881**	**2.3378**	**32.31**

A7: *Carpinus* (350°C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	7.265	37.3471	32.1156	5.2315	2.1335	28.97
2	6.6057	38.3737	33.5135	4.8602	1.7455	26.42
3	8.2457	40.3764	34.2712	6.1052	2.1405	25.96
4	8.3008	39.426	33.2009	6.2251	2.0757	25.01
5	8.2433	39.4206	33.2192	6.2014	2.0419	24.77
6	8.4093	37.8302	31.5815	6.2487	2.1606	25.69
7	8.3573	39.799	33.7623	6.0367	2.3206	27.77
8	6.5154	36.6064	31.9341	4.6723	1.8431	28.29
9	7.9043	40.2879	34.5918	5.6961	2.2082	27.94
10	7.8537	37.0707	31.3174	5.7533	2.1004	26.74
Mean	**7.7701**	**38.6538**	**32.9508**	**5.7031**	**2.077**	**26.756**

A8: *Castanea* (350°C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	5.0653	35.0694	31.9625	3.1069	1.9584	38.66
2	4.5656	36.4309	33.4117	3.0192	1.5464	33.87
3	7.1698	39.3479	34.5606	4.7873	2.3825	33.23
4	6.1855	37.347	33.2346	4.1124	2.0731	33.52
5	4.8871	36.0878	33.2183	2.8695	2.0176	41.28
6	5.4643	34.9101	31.4556	3.4545	2.0098	36.78
7	5.0774	36.5235	34.0554	2.4681	2.6093	51.39
8	4.9033	34.9669	31.7233	3.2436	1.6597	33.85
9	6.5867	39.9889	34.9996	4.9893	1.5974	24.25
10	4.7354	33.9581	31.4451	2.513	2.2224	46.93
Mean	**5.464**	**36.4631**	**33.0067**	**3.4564**	**2.0077**	**37.376**

A9: *Celtis* (350°C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	1.9115	31.0596	29.6535	1.4061	0.5054	26.44
2	1.4952	34.7499	33.735	1.0149	0.4803	32.12
3	1.3512	35.2663	34.3066	0.9597	0.3915	28.97
4	1.7736	43.114	41.8354	1.2786	0.495	27.91
5	2.1031	38.7672	37.215	1.5522	0.5509	26.19
6	1.6319	36.4667	35.2781	1.1886	0.4433	27.16
7	1.8259	38.5182	37.2102	1.308	0.5179	28.36
8	2.0579	33.304	31.8487	1.4553	0.6026	29.28
9	1.1996	34.5829	33.7044	0.8785	0.3211	26.77
10	2.1345	31.4031	29.8469	1.5562	0.5783	27.09
Mean	**1.7484**	**35.7232**	**34.4634**	**1.2598**	**0.4886**	**28.029**

A10: *Corylus* (350˚C) – Specimens 4 & 6 excluded from Means

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	5.0634	35.1271	31.3911	3.736	1.3274	26.13
2	4.7049	36.5698	33.0926	3.4772	1.2277	26.09
3	4.431	36.5758	33.3743	3.2015	1.2295	27.75
4	4.3232	35.4377	33.3706	2.0671	2.2561	52.19
5	5.2305	36.4243	32.7776	3.6467	1.5838	30.28
6	4.57	34.0231	31.7513	2.2718	2.2982	50.29
7	4.6947	36.2093	32.8118	3.3975	1.2972	27.63
8	4.2226	34.2989	31.2736	3.0253	1.1973	28.35
9	4.9144	37.3159	33.6397	3.6762	1.2382	25.20
10	4.0282	33.2231	30.2637	2.9594	1.0688	26.53
Mean	**4.6612**	**35.718**	**32.3281**	**3.39**	**1.2712**	**27.245**

A11: *Crataegus* (350˚C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	7.1103	36.4123	31.2527	5.1596	1.9507	27.43
2	6.7366	40.1081	35.2029	4.9052	1.8314	27.19
3	7.3855	41.4428	35.9962	5.4466	1.9389	26.25
4	7.3852	48.8768	43.7129	5.1639	2.2213	30.08
5	6.2789	43.0151	38.6285	4.3866	1.8923	30.14
6	5.9091	40.8982	36.7722	4.126	1.7831	30.18
7	7.5034	44.3491	38.9705	5.3786	2.1248	28.32
8	6.9335	38.2016	33.2137	4.9879	1.9456	28.06
9	6.9862	40.5475	35.5564	4.9911	1.9951	28.56
10	7.3406	36.7895	31.4952	5.2943	2.0463	27.88
Mean	**6.9569**	**41.0641**	**36.0801**	**4.984**	**1.973**	**28.409**

A12: *Cytisus* (350˚C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	5.7019	35.6588	31.5442	4.1146	1.5873	27.84
2	5.5038	37.2707	33.3115	3.9592	1.5446	28.06
3	5.0638	37.1353	33.4965	3.6388	1.425	28.14
4	5.2629	36.3795	32.6057	3.7748	1.4881	28.28
5	5.2322	36.368	32.7563	3.6117	1.6205	30.97
6	5.8457	35.2458	30.9805	4.2653	1.5804	27.04
7	6.7003	38.1717	33.4933	4.6784	2.0219	30.18
8	4.9169	34.9306	31.5631	3.3675	1.5494	31.51
9	6.1757	38.5197	34.2025	4.3172	1.8585	30.09
10	5.3494	34.5207	30.6783	3.8424	1.507	28.17
Mean	**5.5753**	**36.4201**	**32.4632**	**3.957**	**1.6183**	**29.028**

A13: *Erica* (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	3.9682	33.9256	31.2059	2.7197	1.2485	31.46
2	3.7457	35.5494	33.2471	2.3023	1.4434	38.53
3	4.2009	36.385	33.5755	2.8095	1.3914	33.12
4	2.9183	34.0571	32.2958	1.7613	1.157	39.65
5	3.7472	34.9606	32.3978	2.5628	1.1844	31.61
6	3.3949	32.823	30.5599	2.2631	1.1318	33.34
7	2.5963	34.0736	32.4207	1.6529	0.9434	36.34
8	3.5391	33.5959	31.3252	2.3807	1.1584	32.73
9	3.8745	36.2052	33.5142	2.691	1.1835	30.55
10	3.274	32.5176	30.4747	2.0429	1.2311	37.60
Mean	**3.5359**	**34.4093**	**32.1017**	**2.3186**	**1.2073**	**34.493**

A14: *Fagus* (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	8.5616	38.5057	31.7617	6.744	1.8176	21.23
2	8.1292	39.9089	33.5605	6.3484	1.7808	21.91
3	8.399	40.5117	34.0026	6.5091	1.889	22.50
4	8.6802	39.7931	32.9991	6.794	1.8862	21.73
5	8.9285	40.1773	33.2693	6.908	2.0205	22.63
6	8.5112	37.8772	31.632	6.2452	2.266	26.62
7	8.6613	40.1191	33.4031	6.716	1.9453	22.46
8	9.9176	40.0241	32.3705	7.6536	2.264	22.83
9	7.9471	40.2653	34.3665	5.8988	2.0483	25.77
10	9.2678	38.4724	31.1262	7.3462	1.9216	20.73
Mean	**8.7003**	**37.5655**	**32.8492**	**6.7163**	**1.9839**	**22.841**

A15: *Ficus* (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.0436	33.2936	30.3668	2.9268	1.1168	27.62
2	5.0908	38.4436	34.76	3.6836	1.4072	27.64
3	4.9937	39.0533	35.3669	3.6864	1.3073	26.18
4	4.5846	46.0583	42.7576	3.3007	1.2839	28.00
5	5.345	42.1089	38.2113	3.8976	1.4474	27.08
6	5.3109	40.3451	36.5307	3.8144	1.4965	28.18
7	4.4996	41.3592	38.1582	3.201	1.2986	28.86
8	5.9426	37.2864	32.8906	4.3958	1.5468	26.03
9	4.8051	38.3168	34.8764	3.4404	1.3647	28.40
10	4.7763	34.2252	30.7586	3.4666	1.3097	27.42
Mean	**4.9392**	**39.049**	**35.4677**	**3.5813**	**1.3579**	**27.541**

A16: *Fraxinus* (350˚C) – Specimens 1 & 4 excluded from Means

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	5.6544	35.617	32.9216	2.6954	2.959	52.33
2	3.9362	35.6948	32.8901	2.8047	1.1315	28.75
3	3.0964	35.2339	32.9361	2.2978	0.7896	25.79
4	4.2731	35.4065	33.6226	1.7839	2.4892	58.25
5	5.2136	36.4436	32.6647	3.7789	1.4347	27.52
6	4.4685	33.9349	30.6888	3.2461	1.2224	27.36
7	5.0734	36.6558	32.9508	3.705	1.3684	26.97
8	3.376	33.4345	30.9535	2.481	0.895	26.51
9	3.3546	35.7341	33.2789	2.4552	0.8994	26.81
10	4.5007	33.6845	30.4904	3.1941	1.3066	29.03
Mean	**4.1274**	**35.102**	**32.1067**	**2.9954**	**1.131**	**27.3425**

A17: *Hedera* (350˚C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	4.6393	33.8778	30.5789	3.2989	1.3404	28.89
2	5.6881	39.0436	34.984	4.0596	1.6285	28.63
3	4.861	38.901	35.4537	3.4473	1.4137	29.08
4	4.8233	46.2933	42.9961	3.2972	1.5261	31.64
5	4.8048	41.5337	38.4133	3.1204	1.6844	35.06
6	5.0951	40.0664	36.5788	3.5876	1.5075	29.59
7	3.7423	40.55	38.1189	2.4311	1.3112	35.04
8	4.2589	33.416	30.4955	2.9205	1.3384	31.43
9	4.2761	37.8086	34.894	2.9146	1.3615	31.84
10	4.8453	34.2128	30.8132	3.3996	1.4457	29.84
Mean	**4.7034**	**38.5703**	**35.3326**	**3.2477**	**1.4557**	**31.104**

A18: *Hippophae* (350˚C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	5.9924	35.9083	31.9908	3.9175	2.0749	34.63
2	5.7146	37.4581	33.554	3.9041	1.8105	31.68
3	6.0128	38.1525	34.1155	4.037	1.9758	32.86
4	6.0844	37.1967	33.0775	4.1192	1.9652	32.30
5	6.3523	37.5853	33.2784	4.3069	2.0454	32.20
6	6.4083	35.8259	31.7175	4.1084	2.2999	35.89
7	6.1363	37.6112	33.4584	4.1528	1.9835	32.32
8	6.6797	36.7241	32.4162	4.3079	2.3718	35.51
9	6.1678	38.5454	34.5569	3.9885	2.1793	35.33
10	5.9109	35.2169	31.2662	3.9507	1.9602	33.16
Mean	**6.146**	**37.0224**	**32.9431**	**4.0793**	**2.0667**	**33.588**

A19: *Ilex* (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.4778	35.4634	31.422	4.0414	1.4364	26.22
2	5.873	37.7015	33.4484	4.2531	1.6199	27.58
3	6.0336	38.1784	33.5467	4.6317	1.4019	23.23
4	6.5998	37.7575	32.7117	5.0458	1.554	23.55
5	6.006	37.1884	32.6618	4.5266	1.4794	24.63
6	6.7476	36.2114	30.936	5.2754	1.4722	21.82
7	6.1297	37.6603	33.0437	4.6166	1.5131	24.68
8	5.4491	35.4971	31.4565	4.0406	1.4085	25.85
9	6.3169	38.6732	33.8262	4.847	1.4699	23.27
10	5.9572	35.1948	30.6453	4.5495	1.4077	23.63
Mean	**6.0591**	**36.9526**	**32.3698**	**4.5828**	**1.4763**	**24.446**

A20: *Juglans* (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.6403	34.5647	31.3125	3.2522	1.3881	29.91
2	4.5376	36.2882	33.0112	3.277	1.2606	27.78
3	4.8518	36.9492	33.3809	3.5683	1.2835	26.45
4	4.9516	36.0528	32.5249	3.5279	1.4237	28.75
5	5.6836	36.8579	32.7225	4.1354	1.5482	27.24
6	5.0192	34.3973	30.7427	3.6546	1.3646	27.19
7	4.1832	35.6402	32.8035	2.8367	1.3465	32.19
8	4.8571	34.9144	31.5051	3.4093	1.4478	29.81
9	5.0244	37.3786	33.6976	3.681	1.3434	26.74
10	5.1605	34.3861	30.6401	3.746	1.4145	27.41
Mean	**4.8909**	**35.7429**	**32.2341**	**3.5088**	**1.3821**	**28.347**

A21: *Juniperus* (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	8.1392	38.1353	33.0942	5.0411	3.0981	38.06
2	6.4847	38.2673	33.9235	4.3438	2.1409	33.01
3	6.3156	38.4257	34.1616	4.2641	2.0515	32.48
4	6.5974	37.7221	33.3778	4.3443	2.2531	34.15
5	7.6159	38.8412	34.1654	4.6758	2.9401	38.60
6	5.9638	35.404	31.4885	3.9155	2.0483	34.35
7	7.4101	38.9052	34.4185	4.4867	2.9234	39.45
8	6.8945	36.9696	32.4608	4.5088	2.3857	34.60
9	6.8262	39.2192	34.9857	4.2335	2.5927	37.98
10	6.0488	35.3045	31.2705	4.034	2.0148	33.31
Mean	**6.8296**	**37.7194**	**33.3347**	**4.3848**	**2.4449**	**35.599**

A22: *Larix* (350°C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	5.7094	35.6325	32.4449	3.1876	2.5218	44.17
2	5.7595	37.5389	33.9207	3.6182	2.1413	37.18
3	6.1317	38.1953	34.8271	3.3682	2.7635	45.07
4	5.0447	36.1267	32.954	3.1727	1.872	37.11
5	6.8154	38.0319	33.8536	4.1783	2.6371	38.69
6	5.5004	34.8929	31.3886	3.5043	1.9961	36.29
7	6.4626	37.9315	33.8825	4.049	2.4136	37.35
8	5.024	35.0716	32.1047	2.9669	2.0571	40.95
9	6.3336	38.7459	35.0289	3.717	2.6166	41.31
10	7.2242	36.4054	31.9801	4.4253	2.7989	38.74
Mean	**6.006**	**36.8573**	**33.2385**	**3.6188**	**2.3818**	**39.686**

A23: *Laurus* (350°C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	7.866	37.8246	32.7893	5.0353	2.8307	35.99
2	7.5087	39.3303	34.4811	4.8492	2.6595	35.42
3	7.6562	39.7523	34.8589	4.8934	2.7628	36.09
4	6.0256	37.1803	32.8125	4.3678	1.6578	27.51
5	8.6092	39.8526	34.3562	5.4964	3.1128	36.16
6	8.6114	38.0033	32.4188	5.5845	3.0269	35.15
7	8.0029	39.5285	34.5211	5.0074	2.9955	37.43
8	8.3768	38.4878	33.3806	5.1072	3.2696	39.03
9	7.3787	39.755	35.1658	4.5892	2.7895	37.80
10	7.8424	37.1001	31.4767	5.6234	2.219	28.29
Mean	**7.7878**	**38.6815**	**33.6261**	**5.0554**	**2.7324**	**34.887**

A24: *Olea* (350°C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	8.2128	38.1862	32.1156	6.0706	2.1422	26.08
2	8.5231	40.3092	33.8698	6.4394	2.0837	24.45
3	7.8881	39.9968	34.3955	5.6013	2.2868	28.99
4	8.1791	39.2756	33.2832	5.9914	2.1877	26.75
5	7.7111	38.9031	33.2791	5.624	2.0871	27.07
6	7.605	37.0541	31.3098	5.7443	1.8607	24.47
7	7.7075	39.1671	33.2974	5.8697	1.8378	23.84
8	7.9597	38.0233	31.9503	6.073	1.8867	23.70
9	7.2404	39.6226	34.362	5.2606	1.9738	27.34
10	7.5862	36.8013	31.1343	5.667	1.9192	25.30
Mean	**7.9733**	**38.7339**	**32.8997**	**5.8341**	**2.0256**	**25.799**

A25: *Phillyrea* (350°C)						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	1.3561	31.1683	30.2509	0.9174	0.4387	32.35
2	2.1041	33.7961	32.3659	1.4302	0.6739	32.03
3	1.8113	33.8091	32.63	1.1791	0.6322	34.90
4	1.7598	32.7378	31.5654	1.1724	0.5874	33.38
5	1.65	32.7332	31.6243	1.1089	0.5411	32.79
6	1.2998	30.5705	29.7674	0.8031	0.4967	38.21
7	0.7741	32.0796	31.5496	0.53	0.2441	31.53
8	1.0084	30.9171	30.2874	0.6297	0.3787	37.55
9	1.0113	33.2163	32.5851	0.6312	0.3801	37.59
10	1.1174	30.1553	29.4732	0.6821	0.4353	38.96
Mean	**1.3892**	**32.1183**	**31.2099**	**0.9084**	**0.4808**	**34.929**

A26: *Picea* (350°C)						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.2041	34.1569	31.2283	2.9286	1.2755	30.34
2	3.4038	35.1508	32.8192	2.3316	1.0722	31.50
3	3.8871	36.0047	33.3791	2.6256	1.2615	32.45
4	3.2686	34.3522	32.1382	2.214	1.0546	32.26
5	3.8321	35.0281	32.4633	2.5648	1.2673	33.07
6	4.3635	33.7824	31.0939	2.6885	1.675	38.39
7	3.5833	35.0168	32.5938	2.423	1.1603	32.38
8	3.9444	34.0305	31.5611	2.4694	1.475	37.39
9	3.4088	35.7951	33.6712	2.1239	1.2849	37.69
10	5.3985	34.628	31.2554	3.3726	2.0259	37.53
Mean	**3.9294**	**34.7946**	**32.2204**	**2.5742**	**1.3552**	**34.3**

A27: *Pinus* (350°C)						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.4813	34.5819	31.5647	3.0172	1.4641	32.67
2	5.8367	37.7528	34.1945	3.5583	2.2784	39.04
3	5.4243	37.6482	34.3477	3.3005	2.1238	39.15
4	5.0901	36.3152	32.8204	3.4948	1.5953	31.34
5	4.8649	36.132	32.8171	3.3149	1.55	31.86
6	5.5382	35.0325	31.6667	3.3658	2.1724	39.23
7	5.9333	37.4645	33.7912	3.6733	2.26	38.09
8	5.5477	35.6755	31.8966	3.7789	1.7688	31.88
9	4.8936	37.4681	34.0805	3.3876	1.506	30.77
10	4.5914	34.1447	31.0063	3.1384	1.453	31.65
Mean	**5.2212**	**36.2215**	**32.8186**	**3.403**	**1.8172**	**34.568**

A28: *Pistacia* (350°C)						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	1.6347	30.7722	29.6331	1.1391	0.4956	30.32
2	1.5652	34.8405	33.7766	1.0639	0.5013	32.03
3	1.8479	35.7555	34.45	1.3055	0.5424	29.35
4	1.5101	42.8419	41.8042	1.0377	0.4724	31.28
5	1.3747	37.9787	37.0209	0.9578	0.4169	30.33
6	1.6724	36.5155	35.3363	1.1792	0.4932	29.49
7	1.5088	38.2047	37.1607	1.044	0.4648	30.81
8	1.5661	32.7247	31.64	1.0847	0.4814	30.74
9	1.4616	34.8316	33.7686	1.063	0.3986	27.27
10	1.4132	30.6599	29.6475	1.0124	0.4008	28.36
Mean	**1.5553**	**35.5125**	**34.4238**	**1.0887**	**0.4667**	**29.998**

A29: *Populus* (350°C)						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.1234	34.0826	31.1859	2.8967	1.2267	29.75
2	3.6868	35.4545	32.762	2.6925	0.9943	26.97
3	4.0119	36.0895	33.4209	2.6686	1.3433	33.48
4	4.7117	35.8215	32.6869	3.1346	1.5771	33.47
5	4.3349	35.5454	32.4488	3.0966	1.2383	28.57
6	3.6068	33.0123	30.465	2.5473	1.0595	29.38
7	4.1317	35.6014	32.9236	2.6778	1.4539	35.19
8	3.9189	33.9691	31.1037	2.8654	1.0535	26.88
9	4.1446	36.5624	33.7806	2.7818	1.3628	32.88
10	4.1469	33.3758	30.4455	2.9303	1.2166	29.34
Mean	**4.0818**	**34.9515**	**32.1223**	**2.8292**	**1.2526**	**30.591**

A30: *Prunus* (350°C)						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	6.3174	36.2996	31.9037	4.3959	1.9215	30.42
2	6.5143	38.3948	33.8148	4.58	1.9343	29.69
3	6.6527	38.8615	34.3377	4.5238	2.1289	32.00
4	6.9237	38.1213	33.7883	4.333	2.5907	37.42
5	5.4003	36.6464	33.1222	3.5242	1.8761	34.74
6	5.7277	35.1326	31.4571	3.6755	2.0522	35.83
7	7.1749	38.6782	33.8346	4.8436	2.3313	32.49
8	6.6143	36.6663	32.1748	4.4915	2.1228	32.09
9	6.1419	38.499	34.302	4.197	1.9449	31.67
10	6.5075	35.7714	31.7114	4.06	2.4475	37.61
Mean	**6.3975**	**37.3071**	**33.0447**	**4.2625**	**2.135**	**33.396**

A31: *Pyrus* (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	7.7889	37.7128	32.2412	5.4716	2.3173	29.75
2	6.7348	38.4674	34.069	4.3984	2.3364	34.69
3	7.057	39.1342	33.9059	5.2283	1.8287	25.91
4	7.7822	38.8731	33.2241	5.649	2.1332	27.41
5	6.7358	37.8982	32.9589	4.9393	1.7965	26.67
6	7.2293	36.5781	31.3025	5.2756	1.9537	27.02
7	6.8357	38.2542	33.2683	4.9859	1.8498	27.06
8	6.7906	36.8305	32.368	4.4625	2.3281	34.28
9	7.1411	39.4857	34.1978	5.2879	1.8532	25.95
10	7.9002	37.0625	31.5179	5.5446	2.3556	29.82
Mean	**7.1996**	**38.0297**	**32.9054**	**5.1243**	**2.0753**	**28.856**

A32: *Quercus* Deciduous (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	7.372	37.3617	32.0917	5.27	2.102	28.51
2	7.7085	39.4797	33.6217	5.858	1.8505	24.01
3	7.8824	39.9638	34.0022	5.9616	1.9208	24.37
4	8.5379	39.6892	33.3175	6.3717	2.1662	25.37
5	7.5158	38.7182	33.0315	5.6867	1.8291	24.34
6	8.1539	37.5575	31.6795	5.878	2.2759	27.91
7	8.0714	39.5236	33.4515	6.0721	1.9993	24.77
8	6.8971	36.9558	31.8444	5.1114	1.7857	25.89
9	8.327	40.6937	34.5524	6.1413	2.1857	26.25
10	8.4467	37.6759	31.6732	6.0027	2.444	28.93
Mean	**7.8289**	**38.7619**	**32.9266**	**5.8354**	**2.0559**	**26.035**

A33: *Quercus* Evergreen (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	7.2559	37.189	31.8685	5.3205	1.9354	26.67
2	5.7027	37.4664	33.3053	4.1611	1.5416	27.03
3	6.096	38.2031	33.8532	4.3499	1.7461	28.64
4	7.4631	38.6179	33.0881	5.5298	1.9333	25.90
5	6.1604	37.3321	33.1297	4.2024	1.958	31.78
6	7.5835	37.0086	31.6327	5.3759	2.2076	29.11
7	6.9143	38.3939	33.8076	4.5863	2.328	33.67
8	7.8519	37.9341	32.246	5.6881	2.1638	27.56
9	7.9638	40.398	34.652	5.746	2.2178	27.85
10	6.8118	36.0555	31.5519	4.5036	2.3082	33.89
Mean	**6.9803**	**37.8599**	**32.9135**	**4.9464**	**2.034**	**29.21**

A34: *Rhamnus* (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	6.6464	36.555	32.1663	4.3887	2.2577	33.97
2	6.4404	38.2151	34.0591	4.156	2.2844	35.47
3	8.3616	40.4424	34.7792	5.6632	2.6984	32.27
4	6.8161	37.8855	33.4096	4.4759	2.3402	34.33
5	7.0172	38.1805	33.5489	4.6316	2.3856	34.00
6	7.2672	36.6647	32.0568	4.6079	2.6593	36.59
7	5.8693	37.3003	33.5063	3.794	2.0753	35.36
8	6.2146	36.2535	32.11	4.1435	2.0711	33.33
9	6.4113	38.7176	34.4785	4.2391	2.1722	33.88
10	6.4501	35.5958	31.29	4.3058	2.1443	33.24
Mean	**6.7494**	**37.581**	**33.1405**	**4.4406**	**2.3089**	**34.244**

A35: *Salix* (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.9209	34.8374	31.1416	3.6958	1.2251	24.90
2	4.5548	36.3154	33.0682	3.2472	1.3076	28.71
3	5.8017	37.9316	33.5284	4.4032	1.3985	24.11
4	5.2374	36.3203	32.608	3.7123	1.5251	29.12
5	5.0153	36.237	32.4938	3.7432	1.2721	25.36
6	4.6644	34.0374	30.7291	3.3083	1.3561	29.07
7	5.187	36.6382	32.9433	3.6949	1.4921	28.77
8	4.7634	34.8792	31.2968	3.5824	1.181	24.79
9	5.0648	37.4388	33.627	3.8118	1.253	24.74
10	6.1472	35.3903	30.7791	4.6112	1.536	24.99
Mean	**5.1357**	**36.0026**	**32.2215**	**3.781**	**1.3547**	**26.456**

A36: *Sambucus* (350°C)

Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.5367	35.5282	31.7326	3.7956	1.7411	31.45
2	4.8145	36.593	33.3086	3.2844	1.5301	31.78
3	4.8162	36.9072	33.6246	3.2826	1.5336	31.84
4	4.6767	35.744	32.3946	3.3494	1.3273	28.38
5	4.967	36.1401	32.6285	3.5116	1.4554	29.30
6	5.4323	34.8456	31.0905	3.7551	1.6772	30.87
7	6.3616	37.8175	33.3817	4.4358	1.9258	30.27
8	5.062	35.0888	31.4905	3.5983	1.4637	28.92
9	4.8787	37.2536	33.7738	3.4798	1.3989	28.67
10	5.0793	34.2175	30.7102	3.5073	1.572	30.95
Mean	**5.1625**	**35.0136**	**32.4136**	**3.6**	**1.5635**	**30.243**

A37: *Sorbus* (350°C)						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.6907	35.6015	31.7275	3.874	1.8167	31.92
2	5.5754	37.385	33.6225	3.7625	1.8129	32.52
3	5.8809	38.0705	34.1546	3.9159	1.965	33.41
4	5.2662	36.3767	32.5973	3.7794	1.4868	28.23
5	6.1813	37.4153	32.912	4.5033	1.678	27.15
6	5.6888	35.076	30.9935	4.0825	1.6063	28.24
7	7.147	38.6367	33.5332	5.1035	2.0435	28.59
8	6.0276	36.0891	31.7878	4.3013	1.7263	28.64
9	6.1021	38.4487	34.4106	4.0381	2.064	33.82
10	6.1589	35.3591	30.8612	4.4979	1.661	26.97
Mean	**5.9719**	**36.8459**	**32.66**	**4.1858**	**1.7861**	**29.949**

A38: *Tamarix* (350°C)						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	6.1231	36.1245	31.9369	4.1876	1.9355	31.61
2	6.8055	38.6483	34.4007	4.2476	2.5579	37.59
3	5.6689	37.8142	34.2106	3.6036	2.0653	36.43
4	5.6858	36.7955	33.2808	3.5147	2.1711	38.18
5	6.661	37.8787	33.3833	4.4954	2.1656	32.51
6	6.8924	36.3306	31.6311	4.6995	2.1929	31.82
7	5.4076	36.8956	33.4521	3.4435	1.9641	36.32
8	7.2493	37.4368	32.5178	4.919	2.3303	32.15
9	6.9717	39.4583	34.7674	4.6909	2.281	32.72
10	5.8866	35.1303	31.1448	3.9855	1.9011	32.30
Mean	**6.3352**	**37.2513**	**33.0726**	**4.1787**	**2.1565**	**34.163**

A39: *Taxus* (350°C)						
Specimen Number	**Pre-Burning Weight (g)**	**Pre-Burning Weight inc. Crucible or Foil (g)**	**Post-Burning Weight inc. Crucible or Foil (g)**	**Weight Loss (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	6.4061	36.3562	33.3546	3.0016	3.4045	53.14
2	5.9929	37.8048	34.4506	3.3542	2.6387	44.03
3	6.0469	38.1735	34.3153	3.8542	2.1887	35.04
4	5.6207	36.7929	33.3139	3.479	2.1417	38.10
5	7.6122	38.8525	33.6803	5.1722	2.44	32.05
6	6.8134	36.2201	34.1317	2.0884	4.725	69.35
7	6.4424	37.9681	33.7494	4.2187	2.2237	34.52
8	5.9155	36.0303	32.4804	3.5499	2.3656	39.99
9	5.3268	37.7126	34.6184	3.0942	2.2326	41.91
10	6.3575	35.5398	31.4277	4.1121	2.2454	35.32
Mean	**6.2534**	**37.1451**	**33.5522**	**3.5925**	**2.6606**	**42.345**

A40: *Ulex* (350˚C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	4.887	34.8675	31.4186	3.4489	1.4381	29.43
2	6.1411	37.9042	33.6489	4.2553	1.8858	30.71
3	5.1635	37.2721	33.6306	3.6415	1.522	29.48
4	5.5285	36.6156	32.8392	3.7764	1.7521	31.69
5	5.678	36.885	32.7718	4.1132	1.5648	27.56
6	5.5615	34.9868	30.9453	4.0415	1.52	27.33
7	5.946	37.4352	33.2078	4.2274	1.7186	28.90
8	5.611	35.6553	31.948	3.7073	1.9037	33.93
9	5.0482	37.4211	34.0981	3.323	1.7252	34.17
10	5.2191	34.4321	30.7614	3.6707	1.5484	29.67
Mean	**5.4684**	**36.3475**	**32.527**	**3.8205**	**1.6579**	**30.287**

A41: *Ulmus* (350˚C) – Specimens 6 & 7 excluded from Means

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	5.8476	35.8433	31.8136	4.0297	1.8179	31.09
2	4.529	36.3452	33.2627	3.0825	1.4465	31.94
3	4.7509	36.9137	33.5225	3.3912	1.3597	28.62
4	4.8386	35.9867	32.5151	3.4716	1.367	28.28
5	5.2482	36.4535	32.9403	3.5132	1.735	33.06
6	4.4855	33.9494	31.9538	1.9956	2.4899	55.51
7	4.2169	35.7211	33.9703	1.7508	2.4661	58.48
8	4.8924	35.0235	31.5841	3.4394	1.453	29.70
9	7.4828	39.9134	34.2813	5.6321	1.8507	24.73
10	5.6267	34.7629	30.9896	3.7733	1.8534	32.94
Mean	**5.402**	**36.4053**	**32.6137**	**3.7916**	**1.6104**	**30.045**

A42: *Viburnum* (350˚C)

Specimen Number	Pre-Burning Weight (g)	Pre-Burning Weight inc. Crucible or Foil (g)	Post-Burning Weight inc. Crucible or Foil (g)	Weight Loss (g)	Charcoal Mass (g)	% Weight Remaining
1	5.7776	35.755	31.7704	3.9846	1.793	31.03
2	6.3532	38.2071	33.5773	4.6298	1.7234	27.13
3	5.9819	38.1784	33.9222	4.2562	1.7257	28.85
4	6.5057	37.6546	33.0184	4.6362	1.8695	28.74
5	5.9135	37.1543	32.8492	4.3051	1.6084	27.20
6	5.855	35.248	31.3008	3.9472	1.9078	32.58
7	6.5228	37.9922	33.2829	4.7093	1.8135	27.80
8	5.789	35.8432	31.5839	4.2593	1.5297	26.42
9	7.0989	39.5988	34.4219	5.1769	1.922	27.07
10	6.9957	36.2974	31.5822	4.7152	2.2805	32.60
Mean	**6.2793**	**37.1929**	**32.7309**	**4.461**	**1.8074**	**28.941**

Tables A43-A82: Original burning calculations for 39 genera at 700°C.

A43: ***Acer*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.194	0.0689	1.33
2	5.5686	0.0451	0.81
3	7.1527	0.0559	0.78
4	5.449	0.1324	2.43
5	6.3721	0.1742	2.73
6	4.8448	0.1005	2.07
7	5.0832	0.0503	0.99
8	5.5582	0.0544	0.98
9	5.6799	0.1194	2.10
10	4.9201	0.0107	0.22
Mean	**5.5823**	**0.0812**	**1.444**

A44: ***Alnus*** **(700°C) – Specimen 9 excluded from Means**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.7397	0.0268	0.57
2	3.8836	0.0654	1.68
3	3.6359	0.0576	1.58
4	4.8426	0.2206	4.56
5	4.3789	0.0614	1.40
6	4.8535	0.2386	4.92
7	4.0755	0.0829	2.03
8	4.7991	0.201	4.19
9	4.7364	0.3947	8.33
10	4.512	0.1699	3.77
Mean	**4.4134**	**0.1249**	**2.7444**

A45: ***Amygdalus*** **(700°C) – Specimen 3 excluded from Means**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.5223	0.1113	2.02
2	6.0365	0.1425	2.36
3	4.9614	0.2391	4.82
4	4.9035	0.1504	3.07
5	5.9751	0.1735	2.90
6	5.178	0.1263	2.44
7	5.7412	0.1448	2.52
8	5.4382	0.1366	2.51
9	5.4775	0.1668	3.05
10	5.8269	0.1538	2.64
Mean	**5.5666**	**0.1451**	**2.6122**

A46: *Arbutus* (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.4613	0.2995	5.48
2	4.7034	0.3246	6.90
3	6.0447	0.3461	5.73
4	5.3139	0.2248	4.23
5	4.7487	0.3855	8.12
6	6.6565	0.3287	4.94
7	5.5317	0.3227	5.83
8	4.4365	0.4127	9.30
9	5.143	0.3552	6.91
10	5.6255	0.2589	4.60
Mean	**5.3665**	**0.3259**	**6.204**

A47: *Betula* (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	2.8856	0.0531	1.84
2	5.6679	0.0763	1.35
3	5.2037	0.0738	1.42
4	5.4025	0.1176	2.18
5	5.2364	0.0763	1.46
6	5.9644	0.0883	1.48
7	5.2404	0.1457	2.78
8	5.1069	0.1205	2.36
9	5.2016	0.0563	1.08
10	4.6524	0.0593	1.27
Mean	**5.0562**	**0.0867**	**1.722**

A48: *Buxus* (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	7.5057	0.2096	2.79
2	9.3306	0.2296	2.46
3	7.0384	0.1218	1.73
4	8.1932	0.1668	2.04
5	7.3181	0.2038	2.78
6	6.5045	0.2267	3.49
7	7.4899	0.1881	2.51
8	7.1306	0.1468	2.06
9	7.6848	0.2866	3.73
10	7.8166	0.2159	2.76
Mean	**7.6012**	**0.1996**	**2.635**

A49: *Carpinus* (700°C)

Specimen Number	Pre-Burning Weight (g)	Charcoal Mass (g)	% Weight Remaining
1	7.1059	0.0795	1.12
2	8.2044	0.1628	1.98
3	8.91	0.1588	1.78
4	7.7464	0.1542	1.99
5	7.5893	0.1048	1.38
6	8.2	0.1827	2.23
7	8.1006	0.1766	2.18
8	6.6559	0.1653	2.48
9	6.6491	0.1167	1.76
10	5.6697	0.1025	1.81
Mean	**7.4831**	**0.1404**	**1.871**

A50: *Castanea* (700°C)

Specimen Number	Pre-Burning Weight (g)	Charcoal Mass (g)	% Weight Remaining
1	5.761	0.4125	7.16
2	5.7832	0.391	6.76
3	5.7507	0.3294	5.73
4	4.7731	0.0751	1.57
5	5.6078	0.2102	3.75
6	4.2752	0.143	3.34
7	5.2719	0.0732	1.39
8	5.6728	0.1409	2.48
9	5.495	0.0842	1.53
10	5.1288	0.1461	2.85
Mean	**5.352**	**0.2006**	**3.656**

A51: *Celtis* (700°C) – Specimen 9 excluded from Means

Specimen Number	Pre-Burning Weight (g)	Charcoal Mass (g)	% Weight Remaining
1	1.2489	0.1512	12.11
2	1.6019	0.0951	5.94
3	1.2781	0.1398	10.94
4	1.2004	0.1771	14.75
5	1.4069	0.1681	11.95
6	1.2383	0.1355	10.94
7	1.1857	0.1578	13.31
8	1.2834	0.1379	10.74
9	1.1919	0.2401	20.14
10	1.3958	0.1582	11.33
Mean	**1.3155**	**0.1467**	**11.3344**

A52: ***Cornus*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.6822	0.1814	3.87
2	4.511	0.2048	4.54
3	4.301	0.1511	3.51
4	4.1743	0.2108	5.05
5	4.3403	0.1997	4.60
6	4.5721	0.1296	2.83
7	4.5595	0.2821	6.19
8	4.2808	0.142	3.32
9	3.9757	0.1153	2.90
10	4.1085	0.1657	4.03
Mean	**4.3505**	**0.1783**	**4.084**

A53: ***Corylus*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.9567	0.00	0.00
2	3.8086	0.0475	1.25
3	4.933	0.00	0.00
4	4.7207	0.0715	1.51
5	4.0461	0.00	0.00
6	4.7509	0.0691	1.45
7	4.6531	0.0694	1.49
8	4.1909	0.0784	1.87
9	4.5135	0.0766	1.70
10	4.4625	0.1577	3.53
Mean	**4.5036**	**0.057**	**1.28**

A54: ***Crataegus*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	6.067	0.1702	2.81
2	6.5654	0.1586	2.42
3	6.5383	0.1975	3.02
4	6.5146	0.2061	3.16
5	6.6025	0.1945	2.95
6	7.387	0.1835	2.48
7	7.65	0.2684	3.51
8	6.3926	0.1718	2.69
9	6.7628	0.2033	3.01
10	6.2702	0.2125	3.39
Mean	**6.675**	**0.1966**	**2.944**

A55: ***Cytisus*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.9062	0.1302	2.20
2	5.8204	0.1443	2.48
3	5.8425	0.1401	2.40
4	5.6915	0.1379	2.42
5	5.2905	0.1515	2.86
6	5.9329	0.2092	3.53
7	5.5024	0.2038	3.70
8	6.5463	0.1721	2.63
9	6.1717	0.1344	2.18
10	6.4562	0.1873	2.90
Mean	**5.9161**	**0.1611**	**2.73**

A56: ***Erica*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.6545	0.3646	7.83
2	3.1151	0.1657	5.32
3	3.2703	0.3425	10.47
4	3.6408	0.1891	5.19
5	3.8741	0.2551	6.58
6	4.1364	0.3093	7.48
7	4.1356	0.3117	7.54
8	2.9399	0.2143	7.29
9	3.6737	0.2507	6.82
10	3.4615	0.2342	6.77
Mean	**3.6902**	**0.2637**	**7.129**

A57: ***Fagus*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	8.0998	0.0965	1.19
2	11.8375	0.1585	1.34
3	7.8181	0.0671	0.86
4	9.2864	0.0794	0.86
5	7.4045	0.1426	1.93
6	9.36	0.1946	2.08
7	8.1677	0.0616	0.75
8	10.8105	0.1318	1.22
9	7.8908	0.1144	1.45
10	7.7067	0.1661	2.16
Mean	**8.8382**	**0.1213**	**1.384**

A58: ***Ficus*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.2798	0.3761	8.79
2	4.2062	0.3333	7.92
3	4.5184	0.4493	9.94
4	4.146	0.4209	10.15
5	4.063	0.2767	6.81
6	3.8622	0.3266	8.46
7	3.8734	0.3289	8.49
8	4.1717	0.2973	7.13
9	3.8721	0.3119	8.06
10	3.8136	0.3097	8.12
Mean	**4.0806**	**0.3331**	**8.387**

A59: ***Fraxinus*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	3.9108	0	0.00
2	3.9161	0	0.00
3	4.2046	0.0387	0.92
4	4.8279	0	0.00
5	4.2682	0	0.00
6	4.2057	0	0.00
7	3.9259	0	0.00
8	4.3969	0	0.00
9	4.6822	0.0547	1.17
10	4.2665	0.0784	1.84
Mean	**4.1342**	**0.0172**	**0.393**

A60: ***Hedera*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.1441	0.2402	5.80
2	4.9331	0.4581	9.29
3	4.3666	0.2352	5.39
4	5.5558	0.1342	2.42
5	4.2961	0.1655	3.85
6	5.2238	0.2031	3.89
7	4.3542	0.1902	4.37
8	4.7512	0.2446	5.15
9	4.0662	0.3077	7.57
10	3.8179	0.2165	5.67
Mean	**4.5509**	**0.2395**	**5.34**

A61: ***Hippophae*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.4849	0.021	0.38
2	6.0177	0	0.00
3	6.3687	0.0028	0.04
4	3.7477	0.0326	0.87
5	3.495	0.006	0.17
6	3.599	0.0087	0.24
7	3.6614	0.0066	0.18
8	3.8122	0.0365	0.96
9	3.72	0.0171	0.46
10	3.4606	0.0045	0.13
Mean	**4.3367**	**0.0136**	**0.343**

A62: ***Ilex*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.5513	0.0299	0.54
2	4.829	0.0438	0.91
3	5.545	0.1226	2.21
4	5.1598	0.0493	0.96
5	6.2159	0.1433	2.31
6	5.3301	0.1372	2.57
7	5.5017	0.1125	2.04
8	6.3635	0.1616	2.54
9	5.6553	0.196	3.47
10	5.5867	0.0443	0.79
Mean	**5.5738**	**0.1041**	**1.834**

A63: ***Juglans*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.0074	0.1291	2.58
2	4.7312	0.1645	3.48
3	4.1867	0.1033	2.37
4	5.0429	0.1693	3.36
5	4.5743	0.1723	3.77
6	4.9623	0.1188	2.39
7	4.8406	0.1883	3.89
8	4.7714	0.1657	3.47
9	4.4118	0.1601	3.63
10	4.0005	0.1278	3.19
Mean	**4.6529**	**0.1499**	**3.213**

A64: ***Juniperus*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	6.3948	0.0425	0.66
2	6.4936	0.0413	0.64
3	6.2797	0.0211	0.34
4	5.8842	0.0695	1.18
5	6.3408	0.0407	0.64
6	6.2353	0.0613	0.98
7	6.8871	0.0499	0.72
8	7.2057	0.0731	1.01
9	7.1208	0.0944	1.33
10	5.8187	0.0337	0.58
Mean	**6.4661**	**0.0528**	**0.808**

A65: ***Larix*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.5534	0.0509	1.12
2	5.7344	0.0649	1.13
3	5.0837	0.105	2.15
4	5.1723	0.0905	1.75
5	5.3419	0.1368	2.56
6	5.3272	0.0988	1.85
7	5.3884	0.0911	1.69
8	6.458	0.0913	1.41
9	6.5538	0.0734	1.12
10	6.2215	0.1071	1.72
Mean	**5.5835**	**0.091**	**1.65**

A66: ***Olea*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	7.8991	0.1324	1.68
2	7.2398	0.1792	2.48
3	8.7337	0.158	1.81
4	7.6488	0.1175	1.54
5	8.488	0.2457	2.89
6	7.5542	0.2134	2.82
7	7.2239	0.1387	1.92
8	8.6465	0.2495	2.89
9	7.2125	0.1828	2.53
10	8.2537	0.1775	2.15
Mean	**7.89**	**0.1795**	**2.271**

A67: *Picea* (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.289	0.1328	3.10
2	3.9317	0.1069	2.27
3	3.7694	0.0897	2.57
4	3.6676	0.2266	6.18
5	4.1632	0.0805	1.93
6	4.2804	0.1025	2.39
7	3.8388	0.2089	5.43
8	3.9134	0.172	4.40
9	3.7087	0.1518	4.09
10	3.7092	0.1846	4.98
Mean	**3.9271**	**0.1456**	**3.734**

A68: *Pinus* (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.5422	0.0164	0.30
2	4.3439	0.0096	0.22
3	4.3777	0.0482	1.10
4	4.8327	0.0232	0.48
5	4.8463	0.0258	0.53
6	4.8146	0.0216	0.45
7	4.3639	0.0351	0.80
8	4.5805	0.0324	0.71
9	5.1265	0.0189	0.37
10	4.8039	0.0408	0.85
Mean	**4.7632**	**0.0272**	**0.581**

A69: *Viburnum* (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.9648	0.1251	2.10
2	6.0973	0.112	1.84
3	5.7779	0.298	5.16
4	6.1687	0.2279	3.69
5	8.7376	0.3288	3.76
6	8.1661	0.2809	3.44
7	6.805	0.2411	3.54
8	8.4312	0.3012	3.57
9	8.7589	0.3032	3.46
10	7.062	0.2438	3.45
Mean	**7.197**	**0.2462**	**3.401**

A70: ***Populus*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.6949	0.0597	1.27
2	4.3503	0.0493	1.13
3	3.9262	0.0822	2.09
4	4.6361	0.0471	1.02
5	4.0113	0.0277	0.69
6	4.8614	0.0883	1.82
7	4.3281	0.06	1.39
8	4.3618	0.0406	0.93
9	4.7876	0.0806	1.68
10	4.5562	0.125	2.74
Mean	**4.4514**	**0.0661**	**1.476**

A71: ***Prunus*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	6.3575	0.1375	2.16
2	6.8746	0.1099	1.60
3	5.9783	0.115	1.92
4	5.4738	0.0855	1.56
5	5.9597	0.1672	2.81
6	6.9762	0.0576	0.83
7	6.6412	0.1509	2.27
8	5.6427	0.2128	3.77
9	6.5964	0.1119	1.70
10	6.1239	0.1386	2.26
Mean	**6.2624**	**0.1287**	**2.088**

A72: ***Pyrus*** **(700°C)**			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	7.2724	0.2055	2.83
2	8.1236	0.1577	1.94
3	7.2453	0.2002	2.76
4	6.9041	0.2133	3.09
5	6.5874	0.1263	1.92
6	6.6078	0.2051	3.10
7	6.5874	0.1715	2.60
8	7.0789	0.2141	3.02
9	6.704	0.2021	3.01
10	7.3221	0.1974	2.70
Mean	**7.0433**	**0.1893**	**2.697**

A73: *Quercus* Deciduous (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	8.7855	0.1453	1.65
2	7.4531	0.0926	1.24
3	9.764	0.0873	0.89
4	8.3192	0.1042	1.25
5	9.3897	0.1324	1.41
6	8.2029	0.0888	1.08
7	8.3042	0.1818	2.19
8	6.4153	0.1143	1.78
9	7.7399	0.1347	1.74
10	7.5268	0.1462	1.94
Mean	**8.1901**	**0.1228**	**1.517**

A74: *Quercus* Evergreen (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	7.2336	0.1404	1.94
2	6.8682	0.1832	2.67
3	6.2068	0.2161	3.48
4	6.0041	0.1502	2.50
5	7.4406	0.0733	0.99
6	6.0354	0.1314	2.18
7	7.508	0.2284	3.04
8	7.2044	0.2228	3.09
9	5.6121	0.095	1.69
10	8.0446	0.13	1.62
Mean	**6.8158**	**0.1571**	**2.32**

A75: *Salix* (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.4886	0.0097	0.22
2	5.6621	0.0879	1.55
3	3.6429	0.0289	0.79
4	4.2341	0.1321	3.36
5	4.3123	0.0784	1.82
6	4.3909	0.0938	2.14
7	3.8279	0.0294	0.55
8	4.506	0.0209	0.46
9	4.4667	0.0127	0.28
10	4.3913	0.1088	2.48
Mean	**4.3923**	**0.0603**	**1.365**

A76: *Sambucus* (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	4.9843	0.4545	9.12
2	5.0832	0.2587	5.09
3	4.8417	0.3198	6.61
4	5.0905	0.2844	5.59
5	4.4302	0.374	8.44
6	4.9674	0.3569	7.18
7	4.7725	0.355	7.44
8	5.2527	0.5324	10.14
9	4.5357	0.2495	5.50
10	4.1079	0.2931	7.14
Mean	**4.8066**	**0.3478**	**7.225**

A77: Sorbus (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	3.1687	0.0477	1.51
2	3.8115	0.0611	1.60
3	5.0788	0.0792	1.56
4	6.0102	0.0543	0.90
5	4.8209	0.1611	3.34
6	4.977	0.1707	3.43
7	6.0229	0.189	3.14
8	4.0453	0.0417	1.03
9	6.4907	0.1573	2.42
10	6.9575	0.1482	2.13
Mean	**5.1384**	**0.111**	**2.106**

A78: *Tamarix* (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.9657	0.226	3.79
2	6.3119	0.2965	4.70
3	6.709	0.4444	6.62
4	6.8855	0.4221	6.13
5	5.7589	0.2432	4.22
6	6.3706	0.3941	6.19
7	6.7232	0.4391	6.53
8	6.8689	0.3029	4.41
9	6.6503	0.1641	2.47
10	6.5651	0.4084	6.22
Mean	**6.4809**	**0.3341**	**5.128**

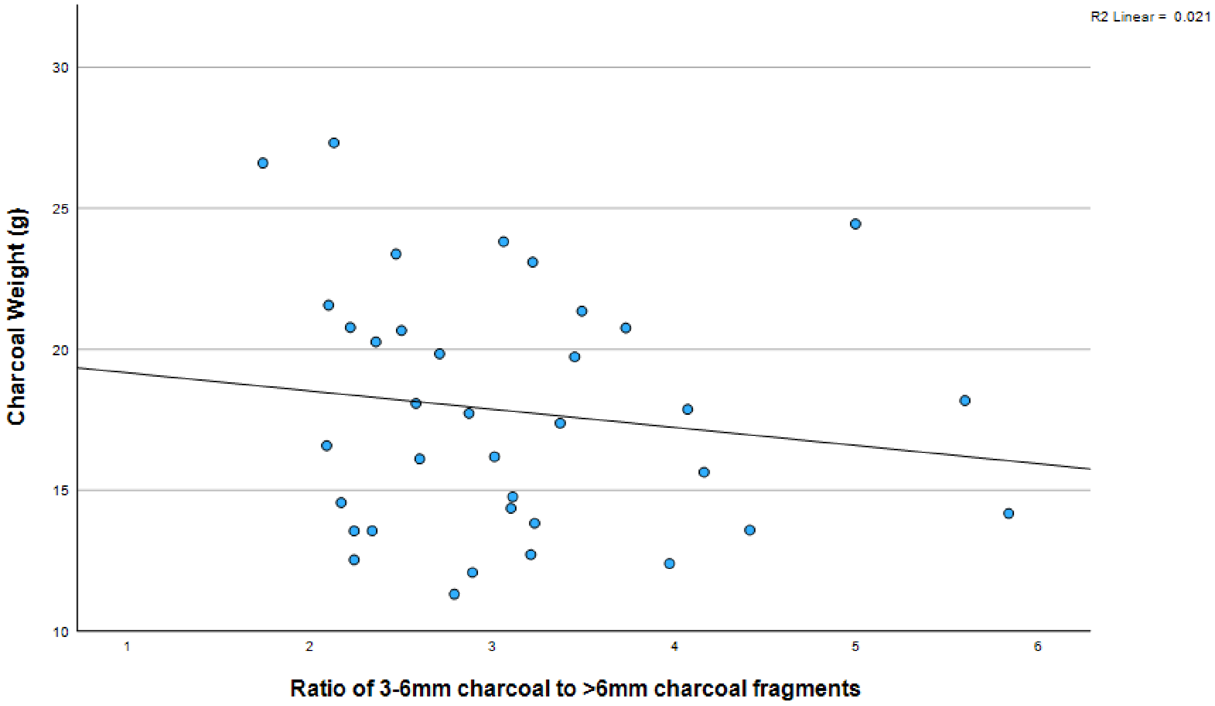
A79: *Taxus* (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.4696	0.1804	3.30
2	6.6745	0.0311	0.47
3	6.154	0.0503	0.82
4	6.0805	0.2585	4.25
5	5.8228	0.2946	5.06
6	5.9604	0.1311	2.20
7	5.9063	0.0093	0.16
8	5.3979	0.1308	2.42
9	5.5757	0	0.00
10	5.4553	0.1195	2.19
Mean	**5.8497**	**0.1206**	**2.087**

A80: *Ulex* (700°C) – Specimen 5 excluded from Means			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	7.1992	0.1814	2.52
2	4.9575	0.1376	2.78
3	6.3735	0.2228	3.50
4	5.2616	0.1474	2.80
5	5.2101	0.0654	1.26
6	5.7363	0.1537	2.68
7	5.9912	0.1886	3.15
8	6.213	0.1555	2.50
9	4.8667	0.1205	2.48
10	4.7198	0.1132	2.40
Mean	**5.7021**	**0.1579**	**2.7567**

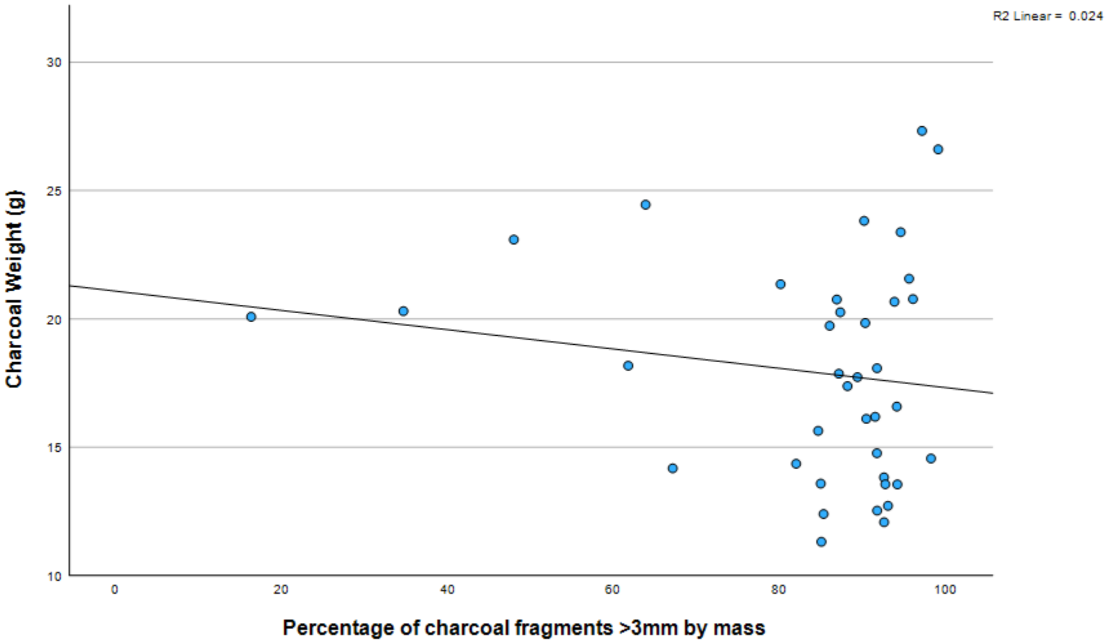
A81: *Ulmus* (700°C)			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	5.0826	0.0591	1.16
2	5.6817	0	0.00
3	4.5188	0.2478	5.48
4	4.8019	0.0323	0.67
5	4.4176	0.0975	2.21
6	4.1681	0.0449	1.08
7	4.7504	0.0313	0.66
8	4.0029	0.0576	1.44
9	3.8847	0.1123	2.89
10	4.5592	0.0526	1.15
Mean	**4.5868**	**0.0735**	**1.674**

A82: *Pistacia* (700°C) – Specimen 1 excluded from Means			
Specimen Number	**Pre-Burning Weight (g)**	**Charcoal Mass (g)**	**% Weight Remaining**
1	1.332	0.3264	24.50
2	2.5914	0.1622	6.26
Mean	**2.5914**	**0.1622**	**6.26**

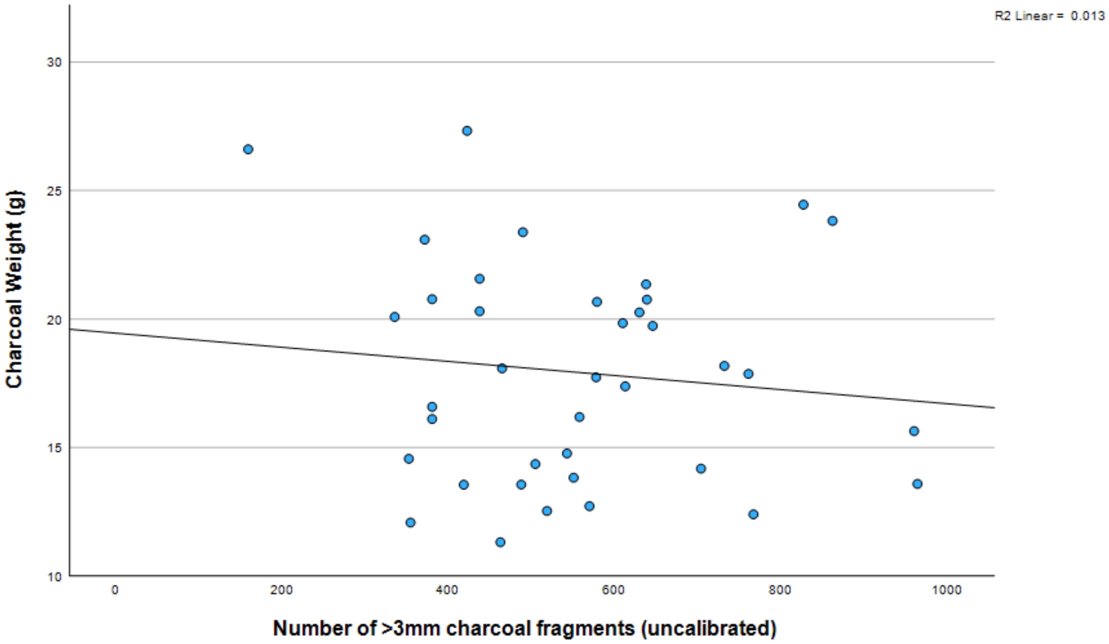
IV: Appendix Four: Charcoal Production and Fragmentation Experiment Graphs.



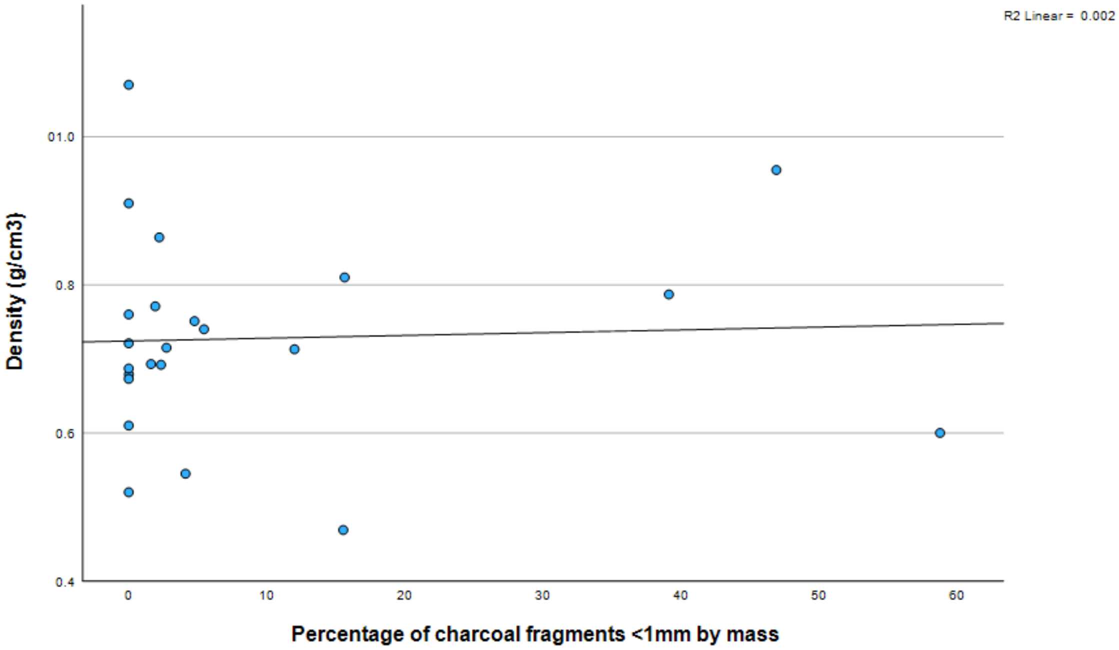
Graph A1: A graph showing a lack of correlation between the mass of charcoal crushed in Experiment 2, and the ratio of Large (>6mm) to Medium (3-6mm) charcoal fragments (R2 = 0.021).



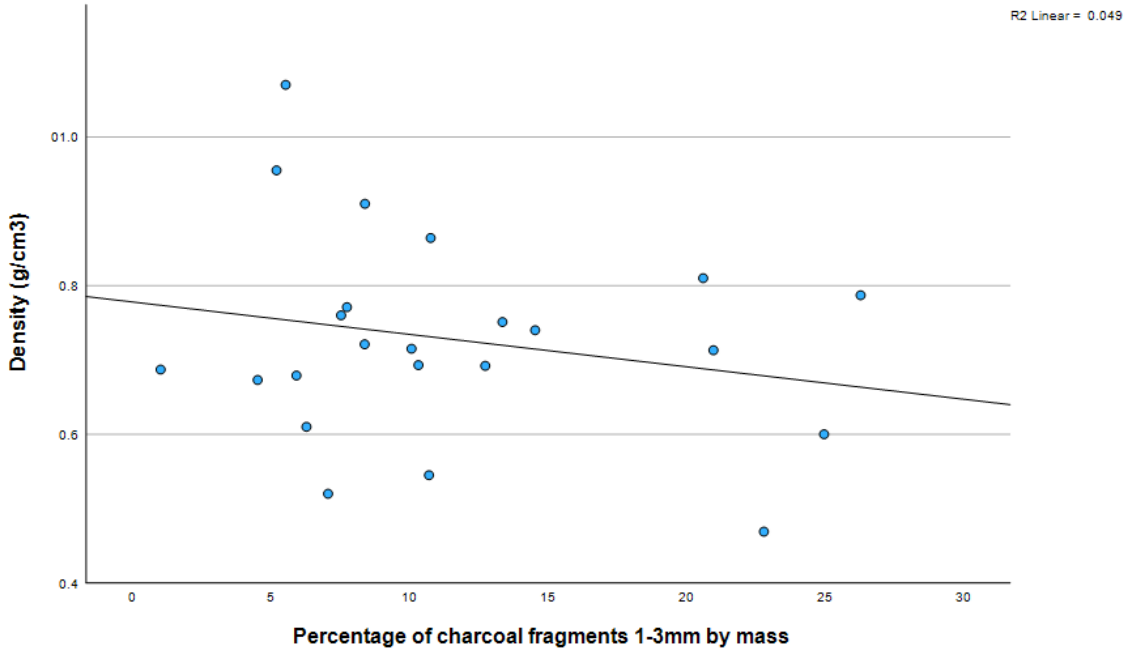
Graph A2: A graph showing a lack of correlation between the mass of charcoal crushed in Experiment 2, and the percentage (by mass) of charcoal fragments over 3mm (R2 = 0.024).



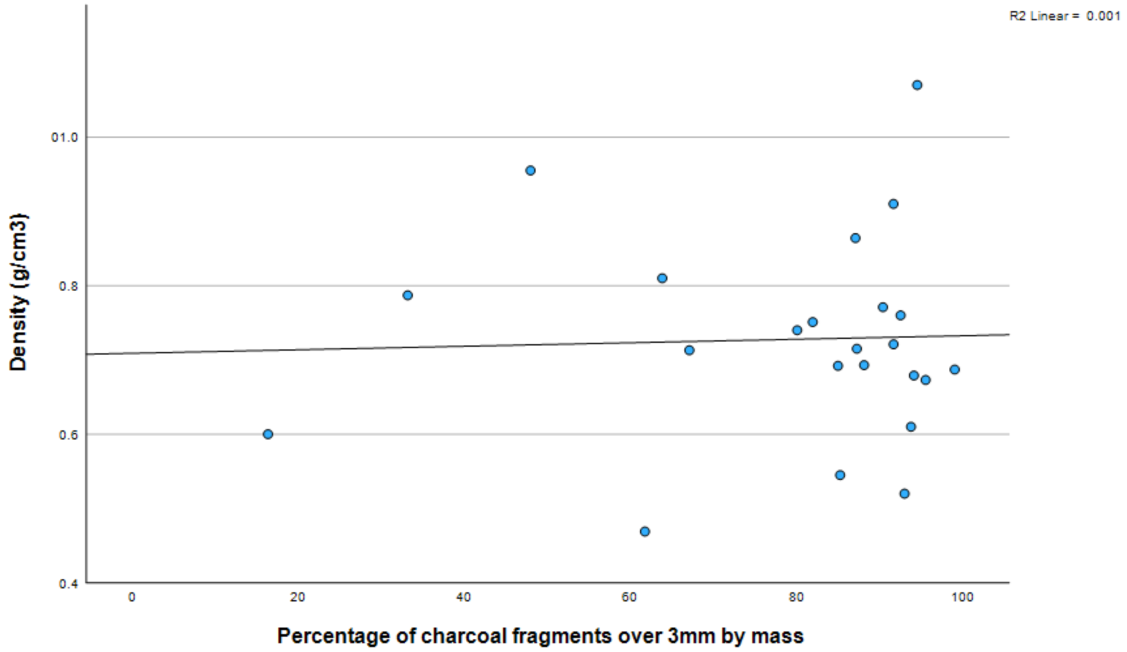
Graph A3: A graph showing the lack of correlation between the mass of charcoal crushed in Experiment 2, and the number of charcoal fragments produced over 3mm (R2 = 0.013).



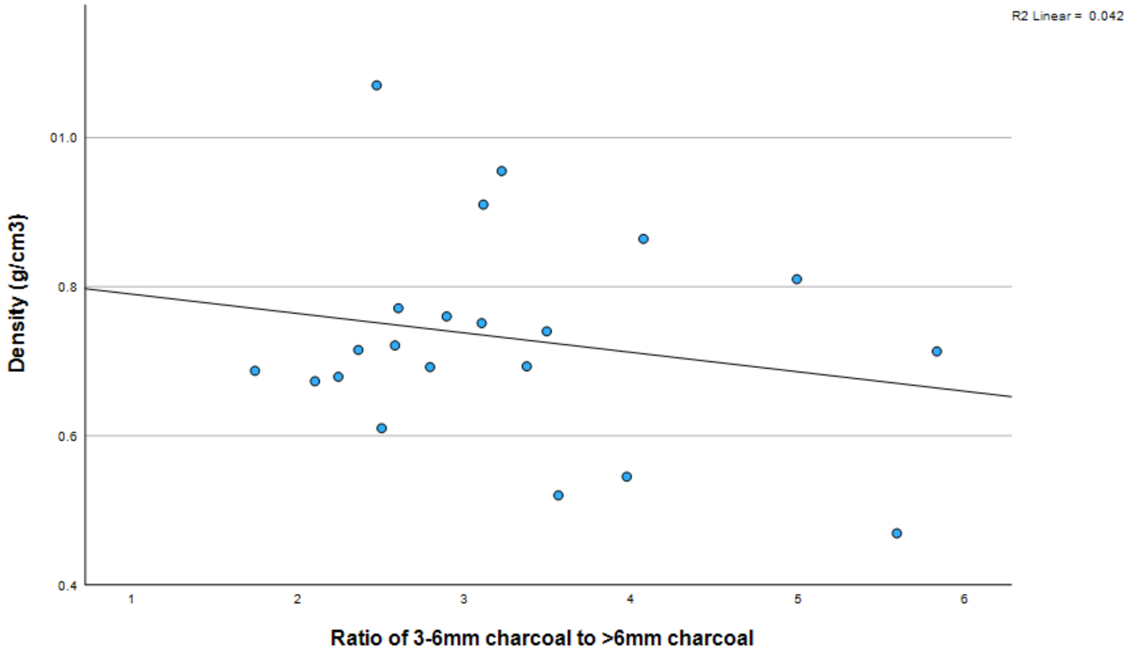
Graph A4: A graph showing the lack of correlation between wood density and the percentage of charcoal fragmented to under 1mm (and thus lost from the recoverable anthracological record). R2 is extremely low (0.002).



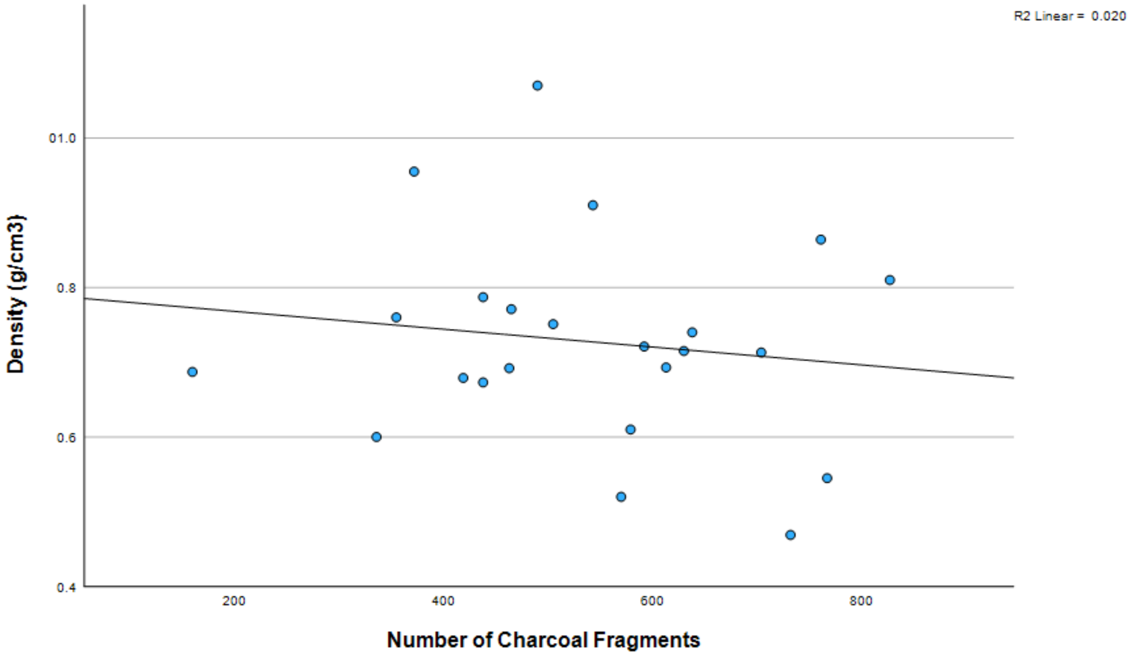
Graph A5: A graph showing the lack of correlation between wood density and the percentage of charcoal fragmented to 1-3mm (R2 = 0.049).



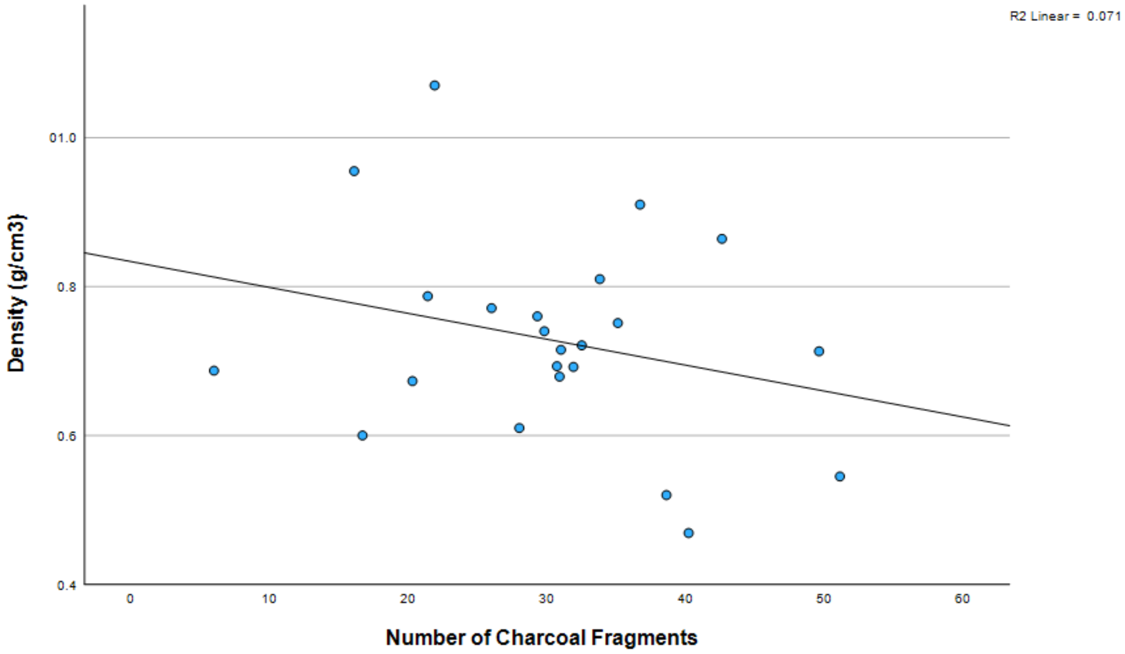
Graph A6: A graph showing the lack of correlation between wood density and the percentage of charcoal fragments remaining over 3mm long (R2 = 0.001).



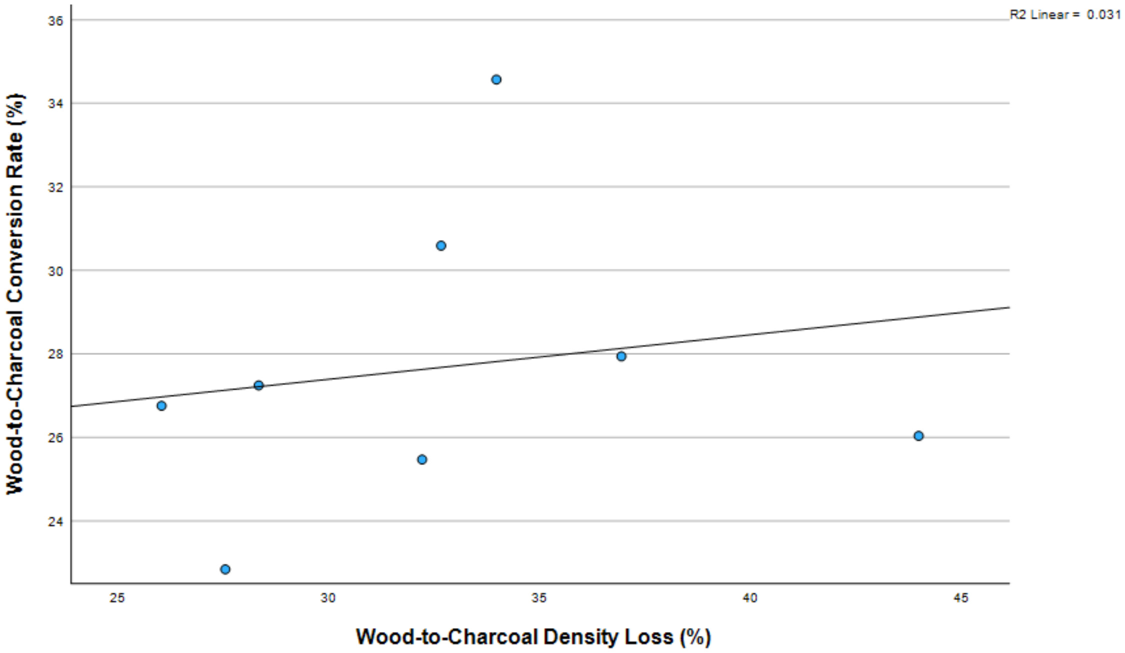
Graph A7: A graph showing the lack of correlation between wood density and the ratio of Large (>6mm) to Medium (3-6mm) charcoal fragments (R2 = 0.042).



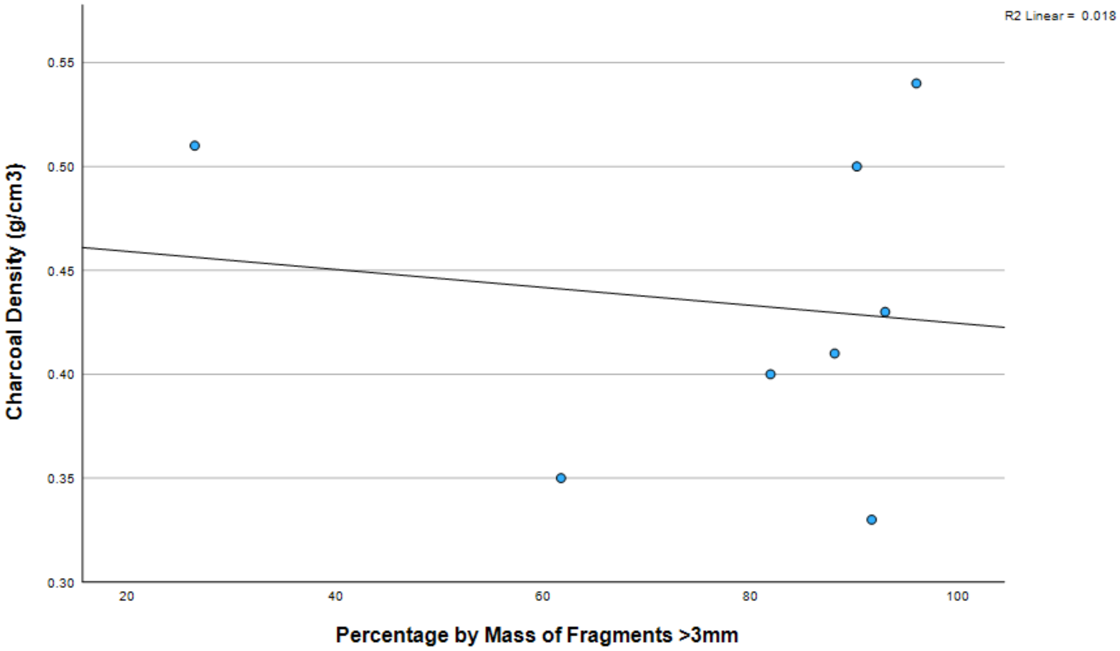
Graph A8: A graph showing the lack of correlation between wood density and the number of charcoal fragments over 3mm (R2 = 0.02).



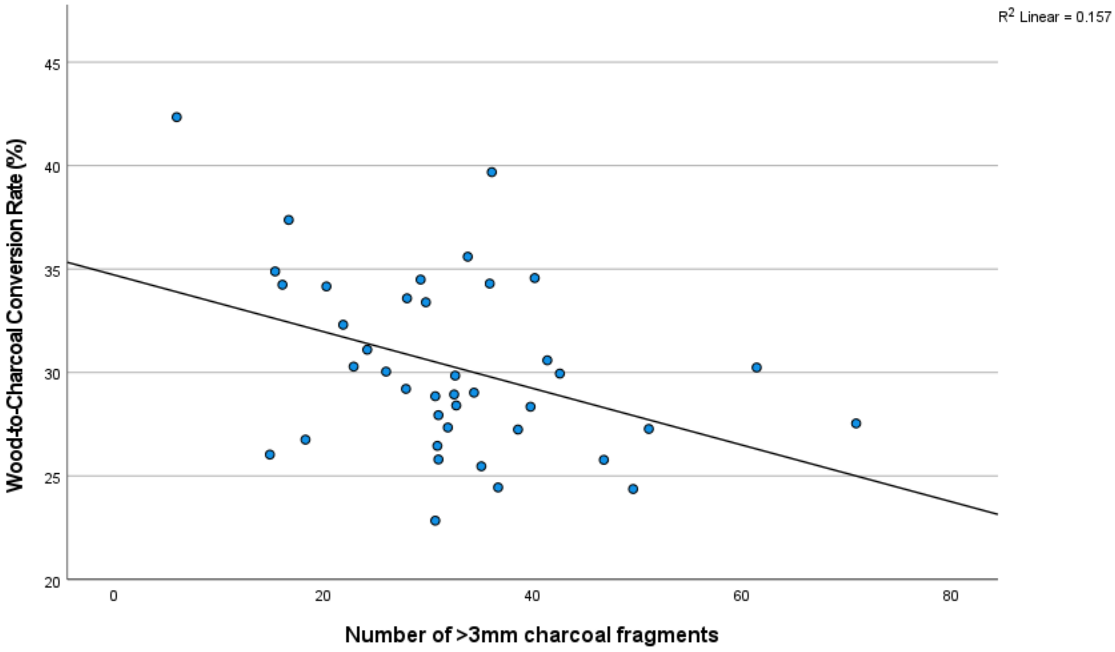
Graph A9: A graph showing the lack of correlation between wood density and the number of charcoal fragments over 3mm, ratioed to a standard charcoal input mass of 1g (R2 = 0.071).



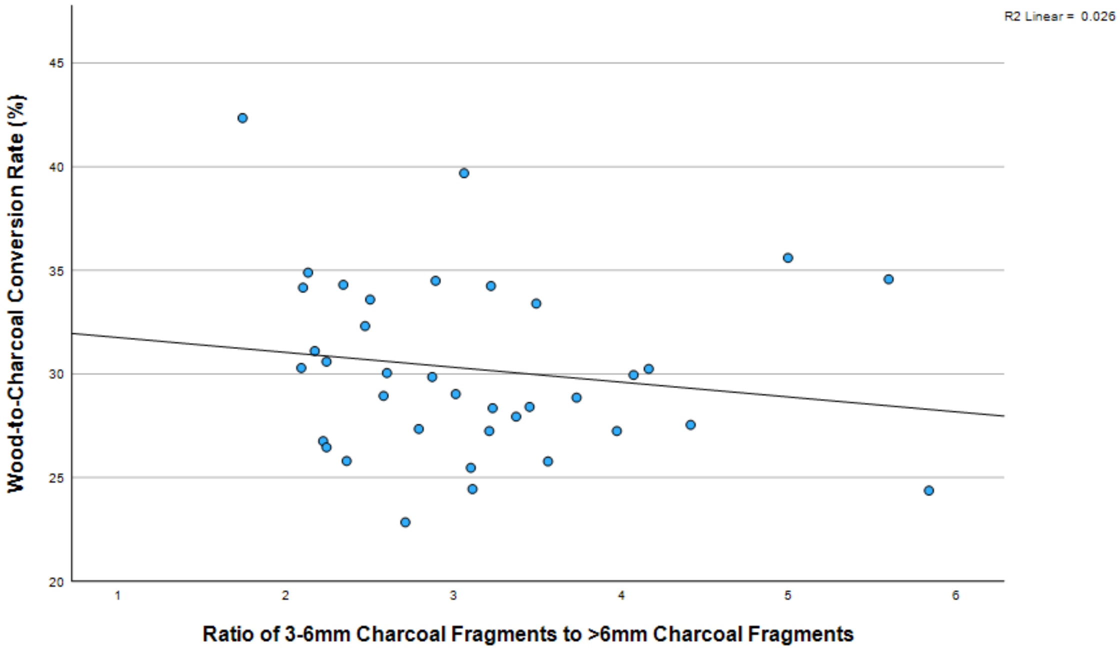
Graph A10: A graph showing the lack of correlation between my wood-to-charcoal conversion rates and Chrzazvez et al.'s (2014) wood-density to charcoal-density conversion rates (R2 = 0.031).



Graph A11: A graph showing the lack of correlation between Chrzazvez' (2014) charcoal densities, and the percentage by mass of Medium and Large fragments remaining in my experiments (R2 = 0.018). This suggests that while charcoal density is important in determining the overall number of fragments, it does not so much determine the size classes that they fall into.



Graph A12: A graph showing the low correlation between predicted wood-to-charcoal conversion rates and the number of >3mm charcoal fragments produced following crushing, ratioed to a standard charcoal input mass of 1g (R2 = 0.157). If the correlation were stronger, it would suggest that woods which produce a lot of charcoal produces charcoal which is less likely to fragment. This indicates that these two factors may to some degree cancel each other out.



Graph A13: A graph showing the lack of correlation between predicted wood-to-charcoal conversion rates and the ratio between Large (>6mm) and Medium (3-6mm) charcoal fragments following crushing (R2 = 0.026). This suggests that the amount of charcoal created in burning will not affect the chance of finding larger or smaller charcoal pieces.

V: Appendix Five: Middle Palaeolithic Site Recalibration Tables.

Table A83-A144: Recalibration tables for 24 Middle Palaeolithic sites, ranked alphabetically and in layer order.

A83: Abric del Pastor Unit IVc (75ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Fraxinus	0.22	0.26	0.67
Juniperus	56.47	52.04	83.17
Pinus	1.34	1.27	2.74
Pistacia	26.79	29.30	5.09
Quercus (Evergreen and Mixed)	14.29	16.26	7.69
Salix-Populus	0.45	0.52	0.38
Taxus	0.45	0.35	0.26

20.43% of charcoal excluded from recalibrations (Angiosperms, Cistaceae, Conifers, *Ephedra*, Euphorbiaceae, Fabaceae, Labiatae, Maloideae, Monocotyledoneae, *Rosa*, Ulmaceae).

A84: Abric del Pastor Unit IVd (75ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Fraxinus	1.29	1.60	3.18
Juniperus	69.92	66.61	83.88
Pinus	4.37	4.29	7.29
Pistacia	18.51	20.92	2.87
Quercus (Evergreen and Mixed)	4.11	4.94	1.83
Salix-Populus	0.51	0.61	0.35
Taxus	1.29	1.03	0.60

21.41% of charcoal excluded from recalibrations (Angiosperms, Cistaceae, Conifers, Fabaceae, Labiatae, *Rosa*).

A85: Abri du Maras Layer 4 (40-46ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Buxus	6.90	7.35	1.62
Juniperus	3.45	3.34	2.65
Pinus	89.66	89.31	95.73

38.30% of charcoal excluded from recalibrations (Angiosperms, Conifers, Fabaceae, Undetermined).

A86: Abrigo de la Quebrada Level VIII (80-130ka BP)

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Celtis	0.30	0.37	0.02	0.40
Juniperus	3.72	3.61	2.72	4.25
Pinus	95.37	95.30	97.13	94.38
Pistacia	0.10	0.12	0.01	0.13
Quercus (Evergreen)	0.41	0.48	0.10	0.68
Viburnum	0.10	0.12	0.02	0.15

18% of charcoal excluded from recalibrations (Angiosperms, Conifer, Ephedra, Ericacea, Fabaceae, Humus, Monocotyledoneae, Rosmarinus).

A87: Aguilon P5 (41.9-50ka BP)

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Pinus	98.20	98.14	99.49
Prunus	1.80	1.86	0.51

1.77% of charcoal excluded from recalibrations (Unidentifiable).

A88: Bojnice III Layer IX (105.1ka BP)

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Juniperus	0.55	0.55	0.63
Picea/Larix	44.20	42.24	15.09
Pinus	51.93	53.11	82.14
Salix/Populus	3.31	4.10	2.14

No charcoal excluded from recalibrations.

A89: Bolomor Cave Levels XI & XIII (160-230ka BP)

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Juniperus	7.41	7.21	5.44
Pinus	92.59	92.79	94.56

50% of charcoal excluded from recalibrations (Angiosperms, Coniferae, Undetermined).

A90: Cova Gran S1B-S1F (37,771-43,259 BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Juniperus	0.75	0.73	0.85
Pinus	98.11	97.93	96.38
Quercus (deciduous)	0.38	0.50	1.33
Rhamnus	0.38	0.38	0.93
Salix/Populus	0.38	0.46	0.50

22.74% of charcoal excluded from recalibrations (Angiosperms, Conifers, Undetermined).

A91: Cova 120 Level IV (57.9ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Arbutus	1.69	2.28	0.22
Corylus	1.69	2.04	1.07
Fraxinus	5.08	6.12	10.43
Juniperus	18.64	17.24	18.61
Phillyrea	15.25	15.04	3.75
Pinus	44.07	41.99	61.20
*Quercus (*Evergreen)	13.56	15.29	4.72

No charcoal excluded from recalibrations.

A92: Cova 120 Level V			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Juniperus	3.57	3.45	2.66
Pinus	92.86	92.46	96.06
Ulmus	3.57	4.09	1.28

No charcoal excluded from recalibrations.

A93: Cova 120 Level VI			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Buxus	2.06	2.13	0.46
Corylus	2.06	2.52	0.96
Fraxinus	9.28	11.31	14.03
Juniperus	2.06	1.93	1.51
Pinus	79.38	76.54	81.17
Quercus (deciduous)	1.03	1.32	0.40
Ulmus	4.12	4.25	1.46

No charcoal excluded from recalibrations.

A94: Cueva Anton Complex AS2 (69.1-72.2ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Juniperus	45.76	44.71	38.65
Pinus	50.85	51.16	59.72
Salix/Populus	3.39	4.13	1.63

25.32% of charcoal excluded from recalibrations (Angiosperm, Conifer, Ephedra).

A95: Cueva Anton Complex AS3 (55-75ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Juniperus	13.70	13.14	10.79
Pinus	79.45	78.48	87.02
Quercus (evergreen and mixed)	6.85	8.38	2.19

18.89% of charcoal excluded from recalibrations (Angiosperm, Artemisia, Conifer).

A96: Cueva Anton Complex AS5 (68.7-77.5ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Erica	0.26	0.25	0.03
Juniperus	15.17	14.20	12.99
Pinus	67.74	65.27	80.66
Prunus	0.39	0.39	0.13
Quercus (evergreen, deciduous, mixed)	15.55	18.84	5.76
Salix-Populus	0.90	1.05	0.44

26.40% of charcoal excluded from recalibrations (Angiosperm, Conifer, Ephedra, Equisetum, Fabaceae, Lamiaceae, Rosaceae).

A97: Cueva del Conde Level N10 (38ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Betula	10.10	13.05	13.95
Castanea	2.02	1.78	4.00
Erica	1.01	0.96	1.23
Fraxinus	1.01	1.22	1.43
Pinus	76.77	73.09	68.20
Quercus (evergreen)	2.02	2.28	3.07
Rhamnus	1.01	0.97	2.26
Sorbus	6.06	6.66	5.86

10.10% of charcoal excluded from recalibrations (Undeterminable).

A98: Cueva del Conde Level N20A (37-38ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Arbutus	1.64	2.17	1.71
Betula	3.01	3.82	4.25
Castanea	0.55	0.48	1.12
Corylus	0.27	0.32	0.32
Crataegus	0.27	0.31	0.37
Cytisus	1.64	1.83	2.08
Erica	1.10	1.03	1.37
Fraxinus	1.10	1.30	1.59
Juniperus	0.27	0.25	0.29
Pinus	63.56	59.40	57.67
Populus	0.27	0.29	0.27
Rhamnus	0.27	0.25	0.61
Salix	3.56	4.35	5.49
Sorbus	21.64	23.34	21.38
Ulex	0.82	0.87	1.48

12.89% of charcoal excluded from recalibrations (Leguminosae, Rosaceae/Pomoideae, Undeterminable).

A99: De Nadale Cave Unit 7 (70.2ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Betula	10.29	13.96	7.48	14.76
Cornus	0.74	0.99	0.23	0.79
Picea/Larix	58.82	54.92	27.35	56.63
Pinus	30.15	30.13	64.95	27.82

13.92% of charcoal excluded from recalibrations (Angiosperms, Conifers).

A100: El Salt Unit VIII (49.2-52.3ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	2.98	3.65	1.24	4.56
Buxus	0.30	0.32	0.07	0.57
Juniperus	1.49	1.43	1.11	1.64
Pinus	93.45	92.40	96.97	89.05
Quercus (deciduous and mixed)	1.49	1.87	0.49	3.68
Ulmus	0.30	0.34	0.11	0.51

0.88% of charcoal excluded from recalibrations (Conifers, Monocotyledoneae).

A101: El Salt Unit IX (52.2ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	7.41	8.91	3.36	10.74
Buxus	0.74	0.77	0.18	1.31
Juniperus	8.15	7.69	6.60	8.50
Pinus	77.78	75.61	87.65	70.28
Pistacia	0.74	0.83	0.08	0.85
Quercus (mixed)	2.22	2.70	0.76	4.71
Salix-Populus	2.96	3.49	1.36	3.60

12.90% of charcoal excluded from recalibrations (Angiosperms, Conifers, Fabaceae).

A102: El Salt Unit Xa (52.3ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	8.46	10.13	3.81	12.06
Juniperus	5.12	4.81	4.12	5.25
Olea	0.79	1.02	0.23	1.21
Pinus	80.51	77.91	90.01	71.50
Pistacia	0.20	0.22	0.02	0.22
Prunus	0.20	0.20	0.06	0.25
Quercus (deciduous, evergreen, mixed)	3.74	4.56	1.31	8.34
Salix-Populus	0.98	1.15	0.45	1.17

13.46% of charcoal excluded from recalibrations (Angiosperms, Conifers, *Ephedra*, Monocotyledoneae).

A103: El Salt Unit Xb AFA 1 (52.3ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Acer	10.31	12.38	4.54
Buxus	0.78	0.81	0.19
Ficus	0.26	0.32	0.02
Juniperus	0.78	0.74	0.61
Pinus	85.90	83.37	93.97
Quercus (deciduous, mixed)	1.83	2.23	0.62
Salix-Populus	0.13	0.15	0.06

5.08% of charcoal excluded from recalibrations (Angiosperms, Conifers, *Ephedra*, Fabaceae).

A104: El Salt Unit Xb AFA 2 (52.3ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Acer	7.39	8.92	3.23
Buxus	1.32	1.38	0.32
Ficus	0.26	0.32	0.02
Hedera	0.33	0.36	0.04
Juniperus	1.06	1.00	0.83
Pinus	87.34	85.24	94.82
Pistacia	0.13	0.15	0.01
Quercus (mixed, deciduous, evergreen)	1.91	2.32	0.62
Salix-Populus	0.26	0.31	0.12

5.19% of charcoal excluded from recalibrations (Angiosperms, Conifers, Fabaceae, Ulmaceae).

A105: El Salt Unit Xb AFA 3 (52.3ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Acer	20.73	24.26	9.90
Buxus	1.63	1.65	0.43
Juniperus	0.41	0.38	0.35
Pinus	74.39	70.35	88.31
Quercus (evergreen, mixed)	2.85	3.36	1.02

4.40% of charcoal excluded from recalibrations (Angiosperms, Conifers, *Ephedra*).

A106: Grotta di Fumane Unit A9 (36.45-46ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Betula	0.40	0.60	0.45	0.65
Larix	52.11	49.92	61.70	52.14
Picea	6.84	7.58	3.58	6.52
Picea/Larix	38.83	39.91	28.18	37.66
Pinus	1.81	1.99	6.09	3.03

17.17% of charcoal excluded from recalibrations (Coniferae, Dicyotyledoneae, Unidentifiable).

A107: Kaldar Cave Layers 4-5 (36,750-54,400BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Amygdalus	35.29	36.81	28.45	34.93
Prunus	52.94	49.35	53.40	51.22
Salix	11.76	13.84	18.15	13.85

46.88% of charcoal excluded from recalibrations (Angiosperms, Unidentified).

A108: Klissoura Cave Layer XXI				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	3.17	3.08	3.71	2.26
Amygdalus	11.11	10.11	7.19	7.04
Juniperus	9.52	7.27	19.92	4.88
Olea	41.27	43.46	30.73	31.83
Prunus	1.59	1.29	1.29	0.98
Quercus (deciduous)	33.33	34.78	37.15	53.00

12.50% of charcoal excluded from recalibrations (Angiosperm, Conifer, Maloideae, Prunoideae).

A109: Klissoura Cave Layer XXg-XXe (123.30ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	14.29	14.32	15.81	11.62
Amygdalus	14.29	13.40	8.74	10.34
Carpinus	7.13	7.46	6.09	10.25
Juniperus	14.29	11.24	28.26	8.36
Olea	28.57	31.00	20.10	25.15
Quercus (deciduous, mixed)	21.43	22.60	21.00	34.28

46.15% of charcoal excluded from recalibrations (Angiosperms, Conifers, Maloideae, Prunoideae).

A110: Klissoura Cave Layers XXd-c (110-123.3ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	19.30	19.10	21.24	14.53
Amygdalus	10.53	9.76	6.41	7.06
Juniperus	10.53	8.18	20.71	5.71
Olea	24.56	26.33	17.19	20.03
Quercus (deciduous and mixed)	35.09	36.63	34.45	52.68

40.00% of charcoal excluded from recalibrations (Angiosperms, Conifers, Maloideae, Prunoideae).

A111: Klissoura Cave Layer XXb-a (95-110ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	13.70	13.27	9.07
Amygdalus	10.96	9.94	6.46
Fraxinus	4.11	4.07	2.70
Juniperus	1.37	1.04	0.65
Olea	24.66	25.87	17.69
Prunus	1.37	1.11	0.79
Quercus (deciduous)	39.73	41.30	58.76
Rhamnus	2.74	2.17	2.86
Ulmus	1.37	1.23	1.00

13.10% of charcoal excluded from recalibrations (Angiosperm, Conifer, Prunoideae, Unidentifiable).

A112: Klissoura Cave Layer XIX (92.84-95ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	1.00	0.95	1.36	0.85
Amygdalus	10.45	9.27	7.87	7.92
Fraxinus	1.00	0.97	5.00	0.85
Juniperus	2.49	1.85	6.06	1.52
Olea	73.13	75.05	63.34	67.41
Pinus	0.50	0.38	1.69	0.26
Prunus	0.50	0.40	0.47	0.37
Quercus (deciduous)	10.95	11.14	14.20	20.82

15.90% of charcoal excluded from recalibrations (Labiatae, Maloideae, Monocot, Prunoideae).

A113: Klissoura Cave Layer XVIII (92.84ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Amygdalus	23.33	21.03	18.44	18.05
Juniperus	0.95	0.72	2.43	0.60
Olea	61.90	64.57	56.28	58.27
Pinus	1.90	1.48	6.75	1.03
Prunus	0.48	0.39	0.47	0.37
Quercus (deciduous)	10.95	11.32	14.90	21.25
Salix	0.48	0.49	0.73	0.44

16.67% of charcoal excluded from recalibrations (Angiosperm, Compositae, Conifer, Prunoideae).

A114: Klissoura Cave Layer XVII (91.15ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Amygdalus	28.57	26.88	18.54
Erica	2.26	1.84	1.41
Laurus	1.50	1.21	1.77
Olea	23.31	25.38	18.41
Pinus	8.27	6.72	3.76
Prunus	0.75	0.63	0.48
Quercus (deciduous)	33.08	35.69	53.86
Rhamnus	1.50	0.86	1.20
Salix	0.75	0.80	0.58

19.88% of charcoal excluded from recalibrations (Angiosperm, Conifer, Prunoideae, Unidentifiable).

A115: Klissoura Cave Layer XVI (82.49ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	18.03	18.30	13.58
Amygdalus	49.18	46.72	32.98
Juniperus	0.55	0.44	0.30
Quercus (deciduous)	30.05	32.73	50.55
Rhamnus	2.19	1.81	2.59

42.27% of charcoal excluded from recalibrations (Angiosperm, Conifer, Labiatae, Prunoideae, Unidentifiable).

A116: Klissoura Cave Layer XV (75.03-82.49ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	37.56	38.69	48.38	36.67
Amygdalus	54.30	52.35	38.66	47.18
Fraxinus	0.90	0.95	4.26	0.87
Olea	0.45	0.50	0.37	0.47
Quercus (deciduous)	6.79	7.51	8.33	14.81

35.19% of charcoal excluded from recalibrations (Angiosperm, Fabaceae, Labiatae, Prunoideae, Unidentifiable).

A117: Klissoura Cave Layer XIV (75.03ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	33.33	34.84	45.36	33.68
Amygdalus	53.54	52.38	40.28	48.15
Juniperus	0.26	0.21	0.63	0.19
Prunus	7.09	6.20	6.67	6.23
Quercus (deciduous, mixed)	5.77	6.37	7.05	11.75

33.97% of charcoal excluded from recalibrations (Angiosperm, Prunoideae, Unidentifiable).

A118: Klissoura Cave Layer XIII (53.93-75.03ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	66.67	67.42	63.74
Amygdalus	23.19	21.95	19.73
Quercus (deciduous, mixed)	8.70	9.44	14.34
Rhamnus	1.45	1.20	2.18

34.29% of charcoal excluded from recalibrations (Angiosperm, Prunoideae, Unidentifiable).

A119: Klissoura Cave Layer XII (53.93ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	28.69	31.47	26.97
Amygdalus	7.38	7.58	6.18
Juniperus	40.16	34.58	27.18
Olea	1.64	1.95	1.67
Pinus	0.82	0.73	0.48
Pistacia	1.64	1.68	1.22
Quercus (deciduous, mixed)	16.39	18.99	31.81
Rhamnus	2.46	2.20	3.63
Ulmus	0.82	0.84	0.86

15.86% of charcoal excluded from recalibrations (Angiosperm, Conifer, Unidentified).

A120: Klissoura Cave Layer XI (46.55ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	24.09	26.97	18.06	23.62
Amygdalus	8.03	8.41	3.33	7.00
Juniperus	49.64	43.62	66.49	35.04
Prunus	2.92	2.73	1.51	2.49
Quercus (deciduous, mixed)	15.33	18.27	10.56	31.85

17.47% of charcoal excluded from recalibrations (Angiosperm, Conifer, Maloideae, Prunoideae, Unidentifiable).

A121: Klissoura Cave Layers X-IX (46.15-46.55ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	4.35	4.54	2.71
Amygdalus	8.70	8.49	4.81
Juniperus	8.70	7.12	3.89
Prunus	17.39	15.17	9.40
Quercus (deciduous)	47.83	53.51	66.36
Rhamnus	13.04	11.18	12.83

17.86% of charcoal excluded from recalibrations (Conifer, Prunoideae, Unidentifiable).

A122: Klissoura Cave Layer VIII-VII (44.8-46.15ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Acer	6.17	6.75	5.23	5.37
Amygdalus	25.93	26.57	12.14	20.10
Juniperus	40.74	35.00	61.68	25.54
Olea	1.23	1.46	0.66	1.16
Quercus (deciduous, mixed)	25.93	30.21	20.29	47.83

44.90% of charcoal excluded from recalibrations (Angiosperm, Conifer, Prunoideae, Unidentifiable).

A123: La Vina Cave Levels XIIIbas, XIV, XV, I.A, I.B		
Genus	**Original %**	**Recalibration for 350°C burning**
Betula	27.52	32.81
Juniperus	13.76	11.74
Pinus	32.72	28.74
Prunus	10.40	9.46
Rhamnus	2.45	2.17
Salix	13.15	15.09

66.08% of charcoal excluded from recalibrations (Angiosperms, Cistacea, Fabaceae, Maloideae, Unidentified).

A124: Llonin Cave Levels VIII CP, VI Gal (43,539BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Betula	31.29	37.81	13.68
Pinus	65.03	57.90	84.29
Salix	3.68	4.28	2.03

81.22% of charcoal excluded from recalibrations (Angiosperms, Fabaceae, Maloideae, Unidentified).

A125: Nesher Ramla Levels I-VIi1 (80-170ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Pistacia	1.72	1.61	0.50	0.84
Prunus	24.14	20.30	21.13	12.94
Quercus (deciduous, mixed)	74.14	78.09	78.37	86.22

61.59% of charcoal excluded from recalibrations (Angiosperms, Undetermined).

A126: Les Canalettes Level 2 (73.5ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Acer	0.37	0.43	0.22
Buxus	22.93	23.17	7.34
Corylus	0.37	0.44	0.24
Fagus	0.37	0.53	0.23
Fraxinus	0.37	0.44	0.79
Juglans	0.37	0.43	0.10
Juniperus	0.37	0.34	0.39
Pinus	57.31	54.12	83.25
Prunus	2.67	2.61	1.08
Pyrus	0.37	0.42	0.12
Quercus (mixed)	13.76	16.26	6.05
Sambucus	0.37	0.40	0.04
Sorbus	0.37	0.40	0.15

12.36% of charcoal excluded from recalibrations (Gymnosperms, Leguminoseae, Rosaceae).

A127: Les Canalettes Level 3			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Betula	0.76	1.01	0.28
Buxus	5.04	5.28	1.21
Corylus	0.76	0.94	0.38
Fraxinus	0.76	0.94	1.23
Juglans	0.76	0.91	0.15
Juniperus	0.76	0.72	0.60
Pinus	86.65	84.86	94.64
Prunus	0.76	0.77	0.23
Quercus (mixed)	3.02	3.70	1.00
Ulmus	0.76	0.86	0.29

0.75% of charcoal excluded from recalibrations (Rosaceae).

A128: Les Canalettes Level 4			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Betula	0.74	1.02	0.26
Buxus	2.09	2.28	0.48
Corylus	0.74	0.96	0.35
Juniperus	0.74	0.73	0.55
Pinus	94.19	93.28	97.91
Prunus	0.74	0.78	0.21
Quercus (mixed)	0.74	0.94	0.23

4.43% of charcoal excluded from recalibrations (Angiosperms, Gymnosperms, Rosaceae).

A129: Pod Hradem Cave Level 11 (45190BP)

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Picea/Larix	76.02	74.67	40.98
Pinus	23.39	24.59	58.43
Salix/Populus	0.58	0.74	0.59

No charcoal excluded from recalibrations.

A130: Pod Hradem Cave Level 10 (43750-45730BP)

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Betula	1.23	1.77	1.56
Juniperus	0.82	0.84	2.21
Picea/Larix	92.21	91.30	74.69
Pinus	5.74	6.08	21.54

No charcoal excluded from recalibrations.

A131: Pod Hradem Cave Level 9

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Betula	0.60	0.85	0.54
Juniperus	0.60	0.61	1.15
Picea/Larix	77.84	76.18	44.97
Pinus	19.16	20.07	51.29
Salix/Populus	1.80	2.28	2.05

No charcoal excluded from recalibrations.

A132: Riparo Bombrini Stratum IV (42911-43087BP)

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Arbutus	12.5	16.22	2.90	10.23
Buxus	25	24.48	13.66	34.96
Corylus	12.5	14.51	14.07	11.76
Erica	12.5	11.46	2.53	12.23
Juniperus	37.5	33.32	66.84	30.83

52.94% of charcoal excluded from recalibrations (Euonymus, Leguminosae, Rosaceae/Maloideae).

A133: Scladina Cave Unit 2B (82ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Betula	1.33	1.79	0.70	1.94
Juniperus	4	3.86	4.48	4.34
Picea	40	40.04	9.69	42.38
Pinus	54.67	54.31	85.13	51.34

No charcoal excluded from recalibrations.

A134: Scladina Cave Unit 4A (88-112ka BP)				
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**	**Recalibration for Fragmentation Bias (and 350°C conversion)**
Fraxinus	3.85	4.26	10.06	3.57
Pinus	30.77	26.95	54.40	17.94
Populus	6.41	6.34	4.46	4.10
Prunus	11.54	10.46	5.68	9.39
Quercus (mixed)	47.44	51.99	25.40	65.00

4.88% of charcoal excluded from recalibrations (Malaceae).

A135: Teixoneres Cave Levels II, IIb and III (38910-48680BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Buxus	28.57	28.65	9.14
Pinus	57.14	53.56	82.92
Quercus (deciduous)	14.29	17.79	7.94

81.58% of charcoal excluded from recalibrations (Angiosperm, Conifer, Undetermined).

A136: Theopetra Cave Layer II3			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Carpinus	22	25.61	17.91
Fraxinus	8	9.11	31.01
Prunus	70	65.28	51.07

No charcoal excluded from recalibrations.

A137: Theopetra Cave Layer II4a (107-150ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Carpinus	2.25	2.61	2.29
Fraxinus	2.25	2.55	10.90
Quercus (deciduous)	16.85	20.08	21.14
Prunus	61.80	57.42	56.33
Sambucus	11.24	11.53	2.96
Ulmus	5.62	5.80	6.39

No charcoal excluded from recalibrations.

A138: Theopetra Cave Layer II4b (107-150ka BP)			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Carpinus	2	2.41	2.26
Prunus	80	77.31	81.01
Quercus (deciduous)	6	7.44	8.36
Sambucus	7	7.47	2.05
Ulmus	5	5.37	6.32

No charcoal excluded from recalibrations.

A139: Theopetra Cave Layer II5			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Carpinus	37	38.68	22.55
Fraxinus	15	15.35	43.51
Juniperus	3	2.36	4.23
Prunus	20	16.75	10.92
Quercus (deciduous)	25	26.86	18.79

No charcoal excluded from recalibrations.

A140: Theopetra Cave Layer II6			
Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Carpinus	42.39	43.19	28.69
Fraxinus	10.87	10.84	35.03
Prunus	10.87	8.87	6.59
Quercus (deciduous)	32.61	34.14	27.22
Ulmus	3.26	2.96	2.47

No charcoal excluded from recalibrations.

A141: Theopetra Cave Layer II7

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Carpinus	10	10.93	8.11
Fraxinus	5	5.35	19.31
Prunus	45	39.42	32.71
Quercus (deciduous)	35	39.33	35.02
Salix/Populus	2	2.05	2.14
Ulmus	3	2.92	2.72

No charcoal excluded from recalibrations.

A142: Theopetra Cave Layer II8

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Fraxinus	21.05	22.06	54.12
Prunus	36.84	31.60	17.83
Quercus (deciduous)	42.11	46.34	28.05

No charcoal excluded from recalibrations.

A143: Theopetra Cave Layer II10

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Juniperus	96	95.75	98.41
Prunus	4	4.25	1.59

No charcoal excluded from recalibrations.

A144: Theopetra Cave Layer II11

Genus	**Original %**	**Recalibration for 350°C burning**	**Recalibration for 700°C burning**
Juniperus	35	32.56	55.05
Quercus (deciduous)	7	8.90	5.86
Prunus	41	39.27	24.96
Salix/Populus	9	10.45	8.05
Ulmus	8	8.82	6.07

No charcoal excluded from recalibrations.

VI: Appendix Six: Wood Traits, Raw Data from Hoare (2020) and Thery-Parisot et al. (2014).

Tables A145-147: Calorific Values, Densities and Ash Contents of individual genera.

Species	**Calorific Value (kJ/g)**	**Mean**
Alnus glutinosa	18.995, 19.8, 19.848, 20.614, 20.94, 21.059, 21.072	20.33
Amygdalus prunus	15.84, 17.376	16.61
Arbutus unedo	17.322, 19.07, 19.142	18.51
Betula pedula	19.761, 21.522	20.64
Carpinus betulus	19.12	19.12
Castanea sativa	17.13, 17.436, 17.56, 17.92, 18.653	17.74
Corylus avellana	16.45	16.45
Fagus sylvatica	17.872, 18, 18.591, 18.894, 19.2, 19.21, 19.256	18.72
Fraxinus excelsior	18.688, 18.709, 18.962, 19.29	18.91
Larix decidua	17.14, 17.68, 17.76, 17.8, 18.66	17.81
Laurus nobilis	17.213, 19.655, 20.069, 20.262, 20.796	19.60
Olea europeae	15.234, 17.556	16.40
Phillyrea latifolia	18.577, 19.175	18.88
Picea abies	18.4, 18.5, 18.62, 18.65, 18.69, 18.94	18.63
Pinus sylvestris	17.85, 17.94, 18.07, 18.32, 18.86, 18.86	18.32
Populus alba	19.133	19.133
Prunus avium	19.622, 19.675, 19.711, 20.061	19.77
Quercus ilex	18.69, 19.568	19.13
Salix atrocinerea	19.018, 19.657, 20.171, 21.327	20.04
Sorbus aria	18.21, 18.236, 19.166, 20.331	18.99
Tamarix ramosissima	17.11, 17.87, 18.28, 19.07	18.08
Taxus baccata	18.301, 20.249, 20.259, 20.561	19.84
Ulex europaeus	20.91, 22.04, 22.08, 22.77	21.95

Species	**Density (g/cm^3)**	**Mean**
Acer campestre	0.6	0.6
Alnus glutinosa	0.316, 0.355, 0.354, 0.513, 0.625, 0.79, 0.8, 0.8, 0.84	0.599
Amygdalus prunus	0.78, 0.79, 0.93	0.833
Arbutus unedo	0.61, 0.64, 0.76, 0.77	0.695
Betula pedula	0.411, 0.512, 0.653, 0.673, 0.801	0.61
Carpinus betulus	0.666, 0.691, 0.71, 0.739, 0.756, 0.756, 0.765, 0.766, 0.784, 0.788, 0.794	0.747
Castanea sativa	0.48, 0.548, 0.59, 0.59, 0.6, 0.61, 0.639	0.58
Corylus avellana	0.52, 0.53, 0.54, 0.547, 0.554, 0.56, 0.58, 0.619	0.556
Crataegus monogyna	0.86	0.86
Fagus sylvatica	0.65, 0.69, 0.73, 0.73, 0.75, 0.76, 0.76, 0.76, 0.8	0.737
Ficus carica	0.52, 0.908, 0.912, 0.917	0.814
Fraxinus excelsior	0.689, 0.79, 0.8, 0.801, 0.81, 0.81	0.783
Hedera helix	0.53, 0.62	0.575
Hippophae rhamnoides	0.574	0.574
Juglans regia	0.526	0.526
Juniperus communis	0.539, 0.575, 0.578, 0.647, 0.736, 0.809	0.647
Larix decidua	0.515, 0.536, 0.56, 0.59, 0.621	0.564
Laurus nobilis	0.76, 0.76, 0.78, 0.8	0.775
Olea europeae	0.49, 0.72, 0.92, 0.93, 0.941, 0.95	0.825
Phillyrea latifolia	0.91	0.91
Picea abies	0.4, 0.415, 0.428, 0.44, 0.454, 0.455, 0.51, 0.529, 0.563, 0.564, 0.572, 0.574, 0.575, 0.6	0.506
Pinus sylvestris	0.35, 0.365, 0.368, 0.448, 0.46, 0.46, 0.492, 0.502, 0.506, 0.513, 0.566, 0.6, 0.625	0.481
Populus alba	0.381, 0.48	0.431
Prunus avium	0.625, 0.753, 0.79, 0.8, 0.83, 0.88	0.78
Pyrus communis	0.72, 0.72, 0.73, 0.73, 0.75	0.73
Quercus ilex	0.69, 0.71, 0.81, 0.88, 0.93	0.804
Salix atrocinerea	0.72, 0.79, 0.8, 0.81	0.78
Sambucus nigra	0.689	0.689
Sorbus aria	0.83, 0.84, 0.85, 0.86, 0.929	0.862
Taxus baccata	0.65, 0.66, 0.66, 0.67	0.66
Ulmus minor	0.609, 0.754	0.682

Species	Ash Content (%)	Mean
Alnus glutinosa	0.5, 0.7	0.6
Amygdalus prunus	1.33, 1.4	1.365
Arbutus unedo	0.83, 1.3, 2.35, 2.27	1.688
Betula pedula	0.1, 0.11, 0.17, 0.17, 0.18, 0.18, 0.18, 0.18, 0.18, 0.18, 0.2, 0.2, 0.21, 0.23, 0.23, 0.24, 0.25, 0.26, 0.26, 0.26, 0.29, 0.29, 0.3	0.211
Carpinus betulus	0.44, 0.52, 1.56	0.84
Castanea sativa	2.26, 7.1, 7.6, 9.5	6.615
Cytisus scoparius	2.45, 2.8, 3, 3.29, 3.52, 3.53, 3.87, 4.25, 4.3, 4.58	3.559
Fagus sylvatica	0.4, 0.4, 0.4, 0.46, 0.5, 0.5, 0.8	0.494
Fraxinus excelsior	0.83	0.83
Hedera helix	5.7	5.7
Hippophae rhamnoides	5.3, 8.1	6.7
Juglans regia	3.67	3.67
Larix decidua	0.15, 0.2, 0.2, 0.25, 0.25, 0.3, 0.4, 0.45, 0.5, 0.55	0.325
Laurus nobilis	2.1	2.1
Olea europeae	1	1
Phillyrea latifolia	0.5, 0.67	0.585
Pinus sylvestris	0.36, 0.45, 0.47, 0.49, 0.55	0.464
Populus alba	1.49, 1.8, 2.07, 2.71, 2.73, 2.75, 2.77, 2.81, 2.83, 3.11, 3.24, 3.27, 3.38, 3.4	2.74
Quercus ilex	1.14, 2.52, 4	2.553
Quercus petraea	0.1, 0.1, 0.2, 0.3, 0.3, 0.3, 0.3, 0.3, 0.4, 0.4, 0.6, 0.9	0.35
Tamarix ramosissima	3.55, 2.99	3.27
Taxus baccata	2.68	2.68
Ulex europaeus	2.8, 3.2, 3.2, 3.3, 3.4, 3.7, 3.8, 4.2, 4.3	3.544

Tables A148-160: The original fire data from Hoare 2020 and Thery-Parisot et al. 2014.

Genus	Top Temperature Attained	Proportion compared to Pinus = 1
Populus	710	0.8050
Betula	780	0.8844
Carpinus	790	0.8957
Quercus	880	0.9977
Pinus	882	1.00
Olea	900	1.0204
Corylus	915	1.0374

Thery-Parisot et al. 2014

Genus	**Top Temperature Attained**	**Proportion compared to Pinus = 1**
Alnus	844	0.9814
Larix	850	0.9884
Pinus	860	1.00
Betula	869	1.0105
Fraxinus	876	1.0186
Fagus	879	1.0221
Quercus	890	1.0349
Picea	1000	1.1628

Hoare 2020, 1m fire, 35kg fuel, 11-13C ambient temperature

Genus	**Top Temperature Attained**	**Proportion compared to Pinus = 1**
Alnus	790	0.8978
Larix	814	0.925
Pinus	880	1.00
Fraxinus	891	1.0125
Betula	906	1.0295
Fagus	908	1.0318
Quercus	961	1.0920
Picea	980	1.1136

Hoare 2020, 1m fire, 35kg fuel, 0-3C ambient temperature

Genus	**Top Temperature Attained**	**Proportion compared to Pinus = 1**
Alnus	562	0.7483
Quercus	596	0.7936
Larix	618	0.8229
Picea	642	0.8549
Fraxinus	651	0.8668
Fagus	729	0.9707
Pinus	751	1.00
Betula	816	1.0866

Hoare 2020, 0.5m fire, 7kg fuel.

Genus	**Burning Duration (minutes)**	**Proportion compared to Pinus = 1**
Corylus	430	0.9620
Populus	440	0.9843
Pinus	447	1.00
Betula	450	1.0067
Olea	460	1.0291
Quercus	650	1.4541
Carpinus	730	1.6331

Thery-Parisot et al. 2014

Genus	**Burning Duration (minutes)**	**Proportion compared to Pinus = 1**
Alnus	125	0.7143
Picea	135	0.7714
Betula	170	0.9714
Pinus	175	1.00
Quercus	190	1.0857
Fagus	190	1.0857
Larix	205	1.1714
Fraxinus	220	1.2571

Hoare 2020, 1m fire, 35kg fuel, 11-13C ambient temperature.

Genus	**Burning Duration (minutes)**	**Proportion compared to Pinus = 1**
Alnus	90	0.4615
Picea	140	0.7179
Betula	150	0.7692
Fagus	170	0.8718
Fraxinus	170	0.8718
Larix	185	0.9487
Pinus	195	1.00
Quercus	220	1.1282

Hoare 2020, 1m fire, 35kg fuel, 0-3C ambient temperature.

Genus	**Burning Duration (minutes)**	**Proportion compared to Pinus = 1**
Picea	60	0.4444
Alnus	75	0.5556
Betula	85	0.6296
Fagus	105	0.7778
Larix	130	0.9629
Pinus	135	1.00
Fraxinus	140	1.0370
Quercus	155	1.1481

Hoare 2020, 0.5m fire, 7kg fuel.

Genus	**Charring Rate (mm/min)**	**Proportion compared to Quercus = 1**
Acer	9.8367	0.9136
Fagus	10.1767	0.9452
Picea	10.1867	0.9461
Fraxinus	10.1967	0.9471
Quercus	10.7667	1

Hugi et al. 2007.

Genus	**Charring Rate (mm/min)**	**Proportion compared to Pinus = 1**
Pinus	0.8924	1.00
Acer	1.0465	1.1727
Picea	1.179	1.3212
Quercus	1.1985	1.343

White and Nordheim 1992.

Genus	**Charring Rate (mm/min)**	**Proportion compared to Pinus = 1**
Pinus	1.295	1.00
Acer	1.508	1.1645
Picea	1.698	1.3112
Quercus	1.7267	1.3334

White 1988.

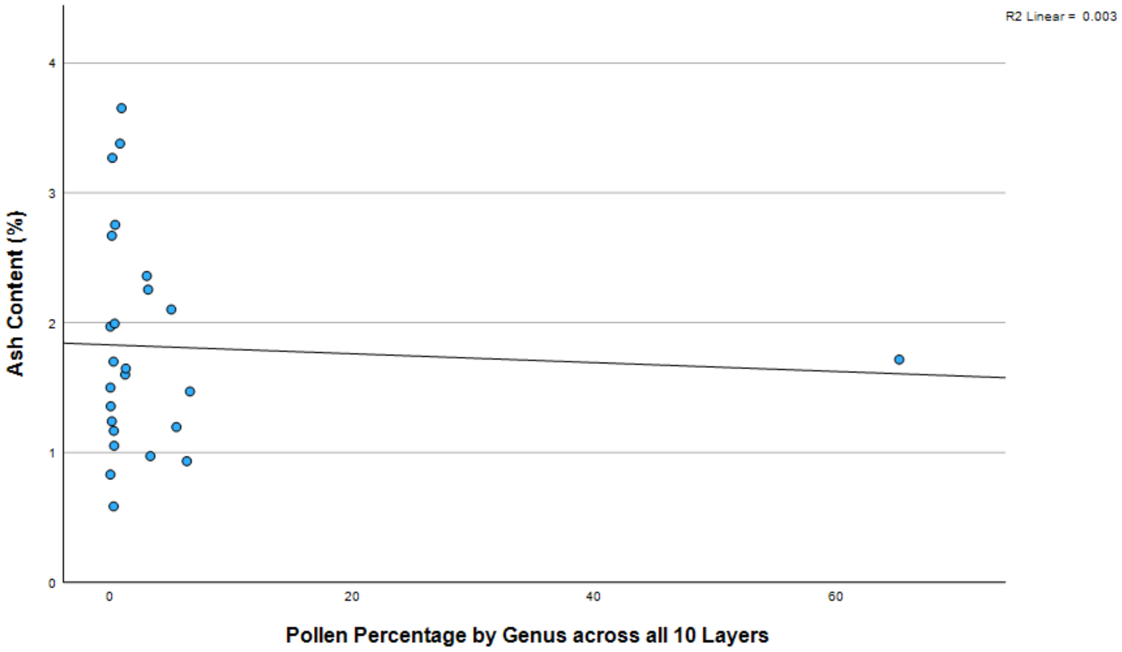
Genus	**Times of flame penetration to 0.5 inches (mins)**	**Proportion compared to Pinus = 1**
Acer	4.5	1.00
Pinus	4.5	1.00
Picea	4.5	1.00
Betula	5.5	1.2222
Quercus	7	1.5556

Bryan and Doman 1940.

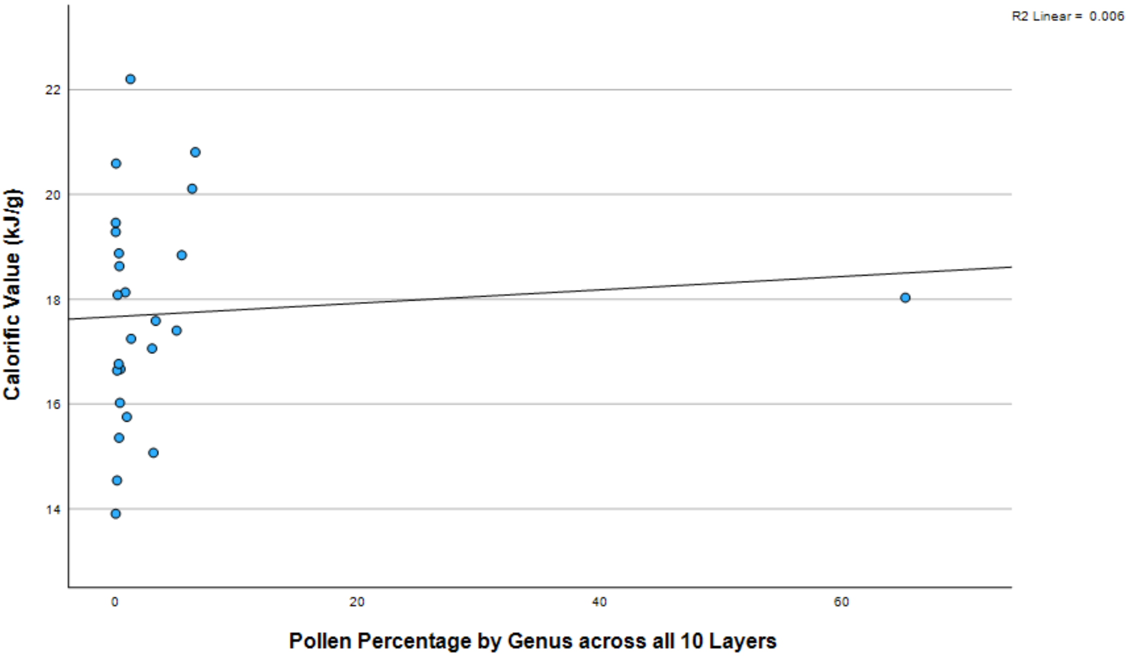
Genus	**Times of flame penetration to 0.75 inches (mins)**	**Proportion compared to Pinus = 1**
Acer	21.6	0.926
Pinus	23.325	1.00
Castanea	26.1	1.119
Picea	26.5	1.1361
Quercus	27.45	1.1768
Betula	27.5	1.179

McNaughton 1942.

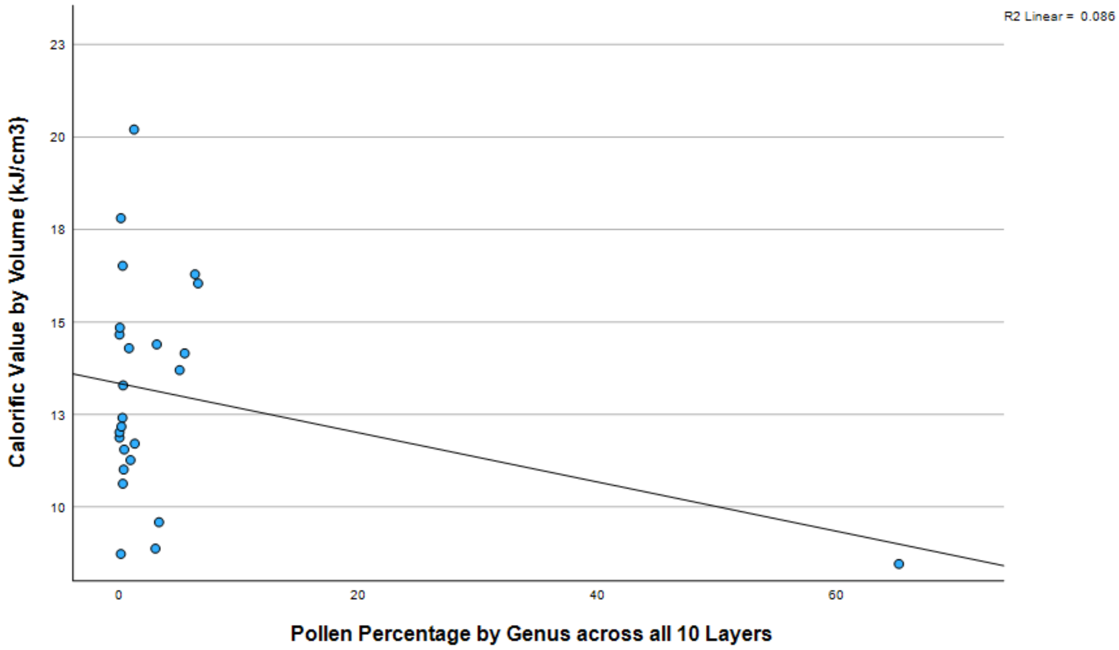
VII: Appendix Seven: Miscellaneous Graphs.



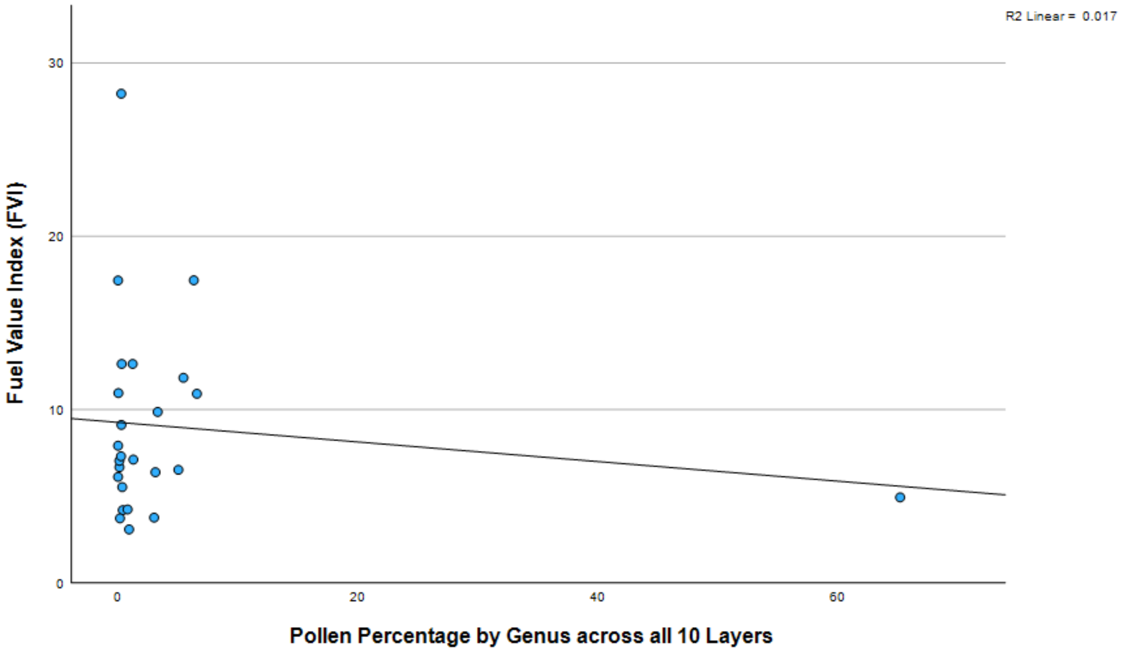
Graph A14: A graph showing that random selection from the Middle Palaeolithic Iberian landscape would not have caused burning of particularly high- or low-ash fuelwoods. The R2 value is particularly low (0.003).



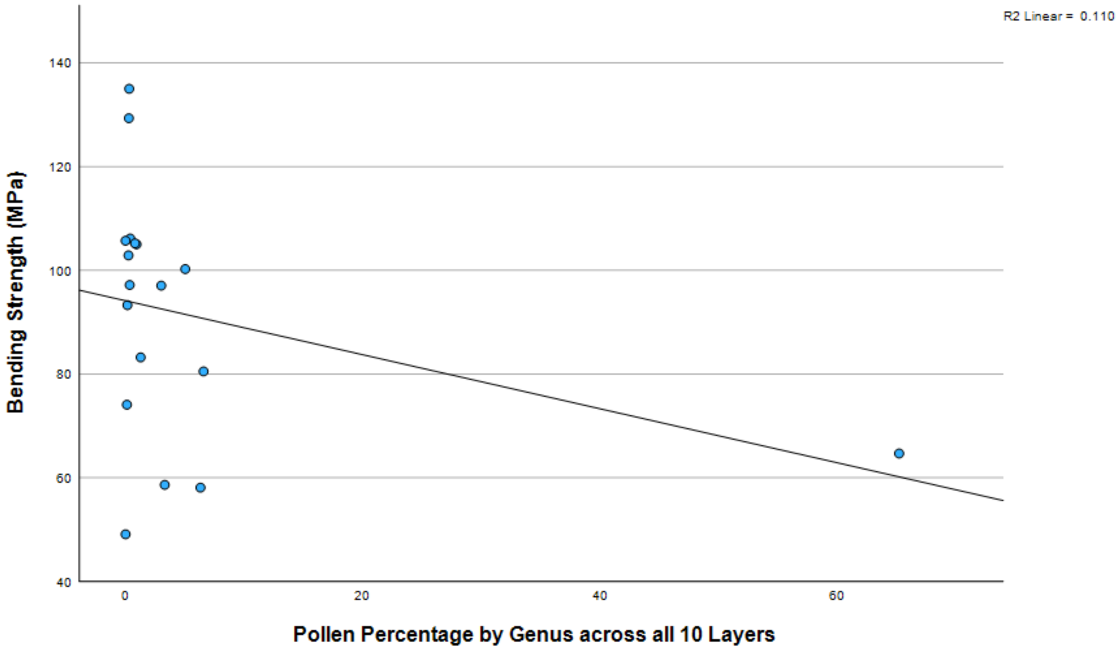
Graph A15: A graph showing that the Middle Palaeolithic Iberian landscape did not tend to contain particularly high- or low-calorie fuelwoods (R2 = 0.006). Pine, the most common landscape wood, had a very average value.



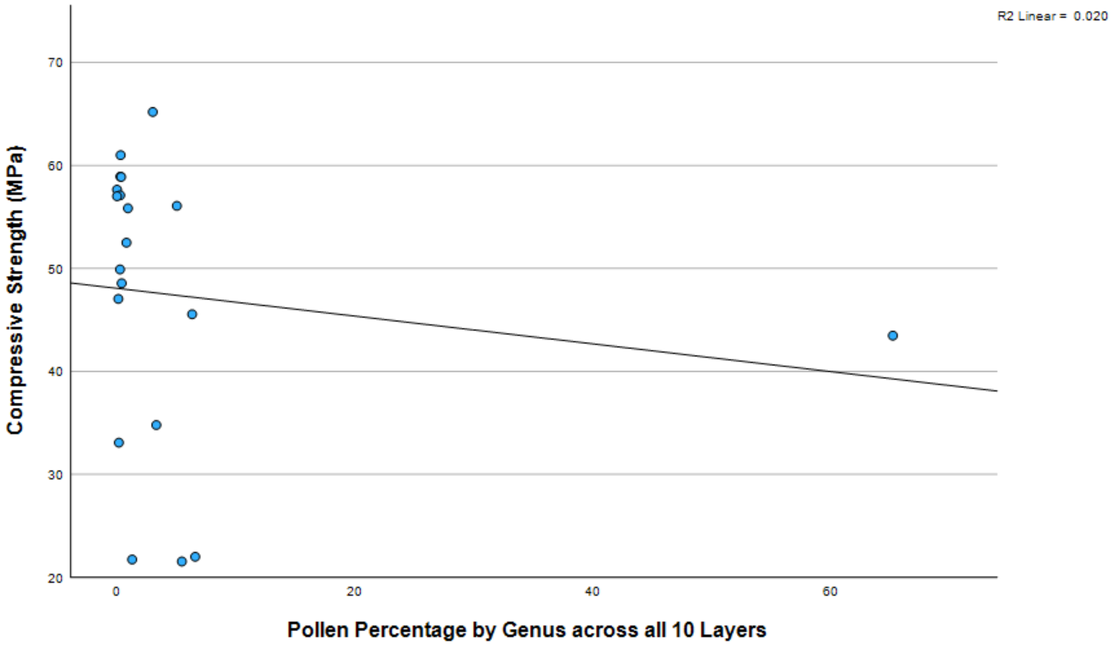
Graph A16: A graph showing that across the natural Middle Palaeolithic Iberian landscape, the dominant pine tends to have a low Fuel Value Index (FVI), although this is not a statistically-significant trend (R2 = 0.017).



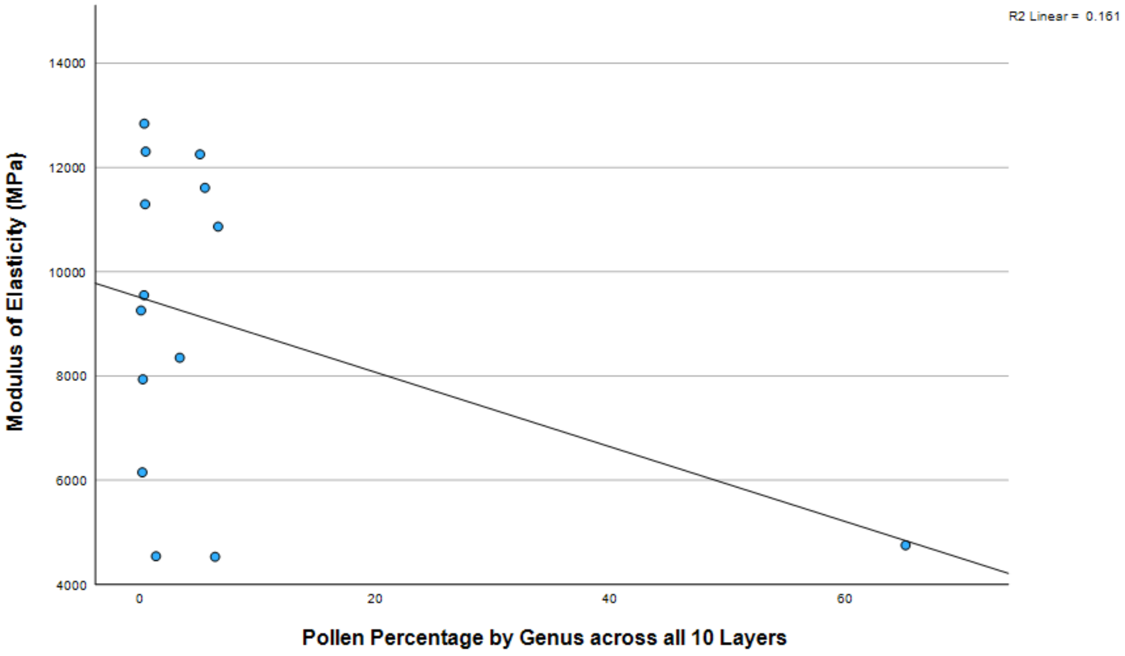
Graph A17: A graph showing that, due to the prevalence of low-density pine in Middle Palaeolithic Iberia, random gathering in such a landscape would tend towards woods that have a low calorific value by volume (R2 = 0.085).



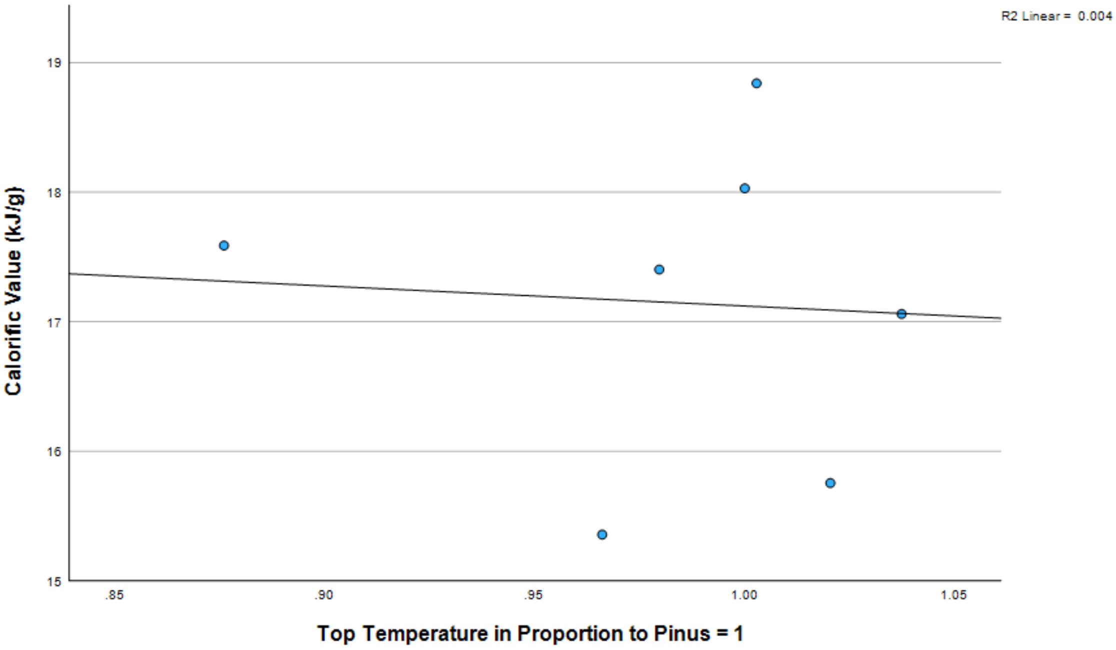
Graph A18: A graph showing the random selection of wood from a Middle Palaeolithic Iberian landscape would select wood with a low bending strength, although this trend is not statistically-significant (R2 = 0.110).



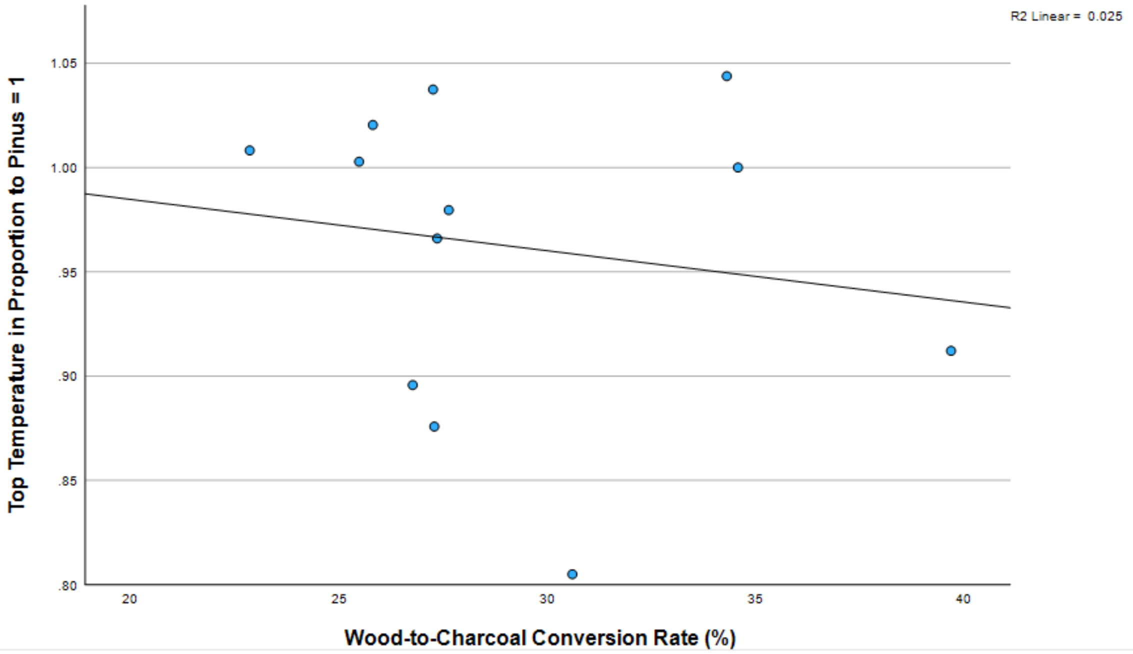
Graph A19: A graph showing that the natural Middle Palaeolithic Iberian landscape did not contain predominantly high- or low-compressive strength woods (R2 = 0.02).



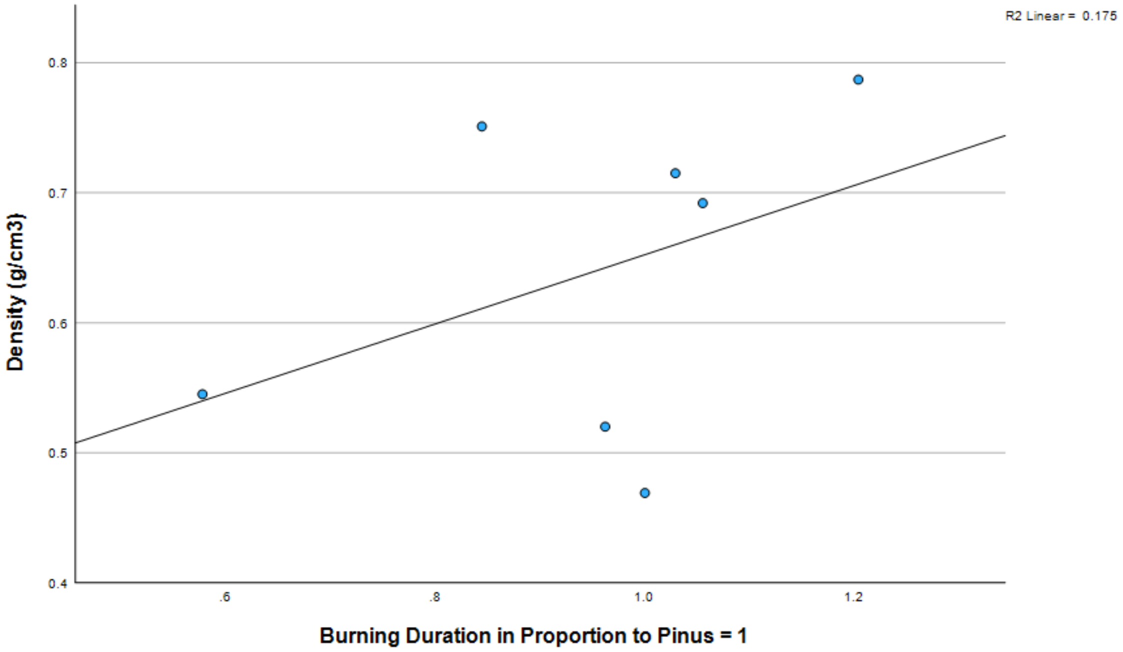
Graph A20: A graph showing that Middle Palaeolithic Iberian landscapes were dominated by woods with low moduli of elasticity, although this trend is not statistically significant (R2 = 0.161).



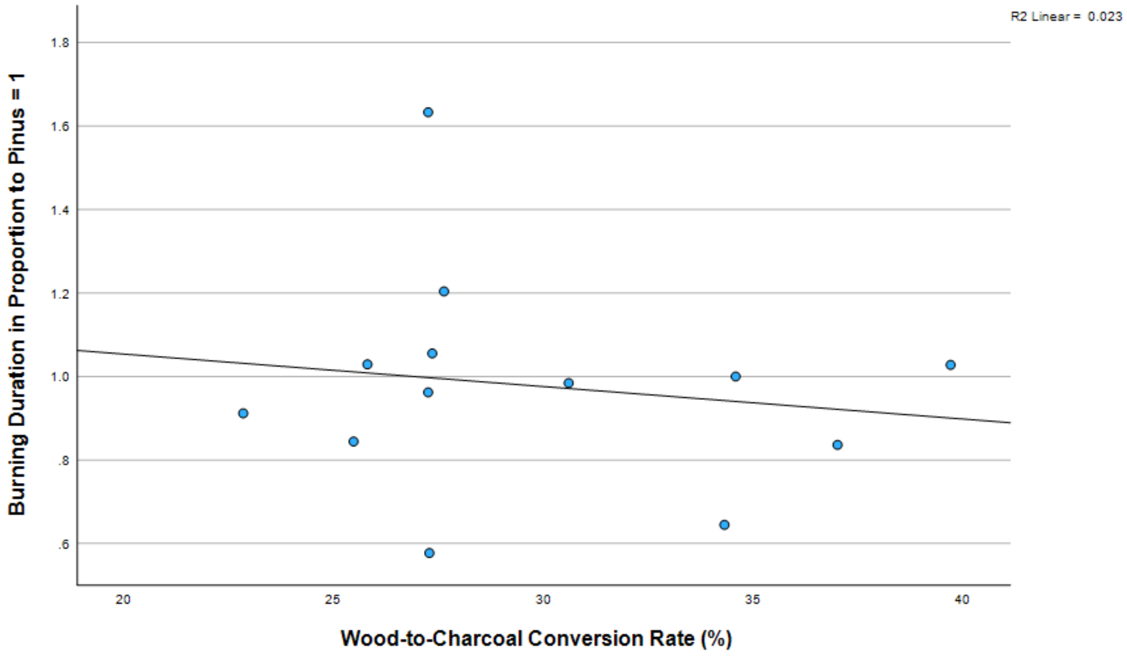
Graph A21: A graph showing the lack of correlation between a genus's calorific value and the top temperature that can be obtained in a fire exclusively composed of that genus (R2 = 0.004).



Graph A22: A graph showing the lack of correlation between the wood-to-charcoal conversion rate of a genus, and the top temperature that can be obtained in a fire exclusively composed of that genus (R2 = 0.025). This is to be expected as there is no indication that wood-to-charcoal conversion rate is correlated with any burning attributes. Furthermore, in my experiments, top temperatures never varied as the wood was not the temperature-controlling variable.

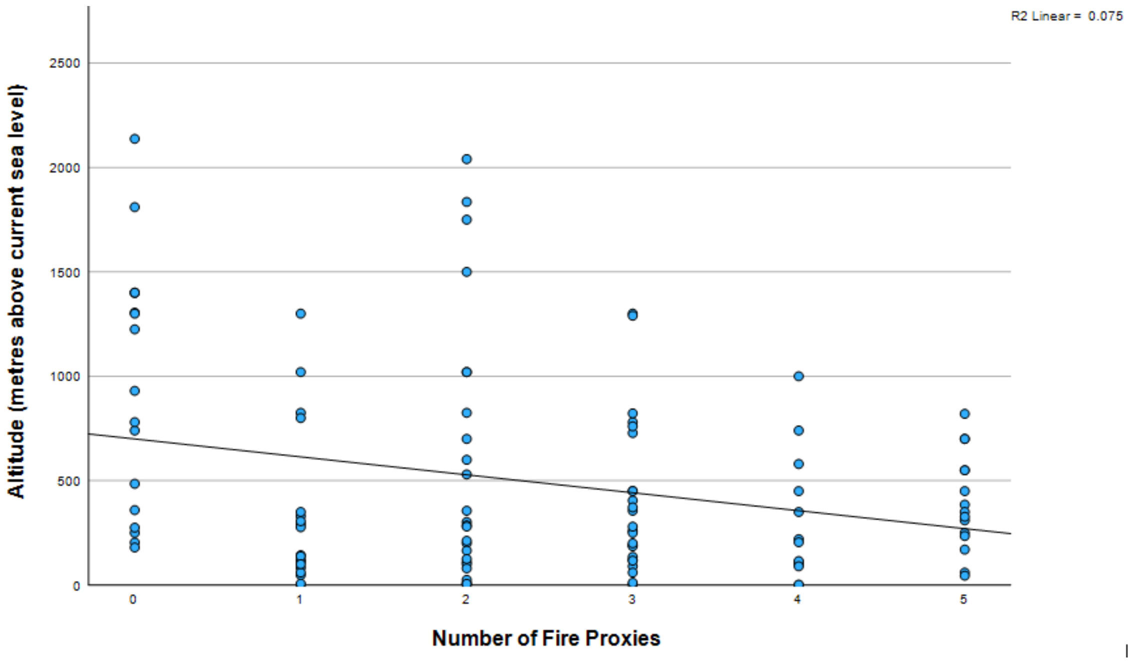


Graph A23: A graph showing that density has little effect on the burning duration of various fuels, despite in theory denser woods burning more slowly (R2 = 0.175). This lack of correlation may result from different (random) fuel loading densities onto the fire having a greater effect than the wood's internal density per piece of fuel.

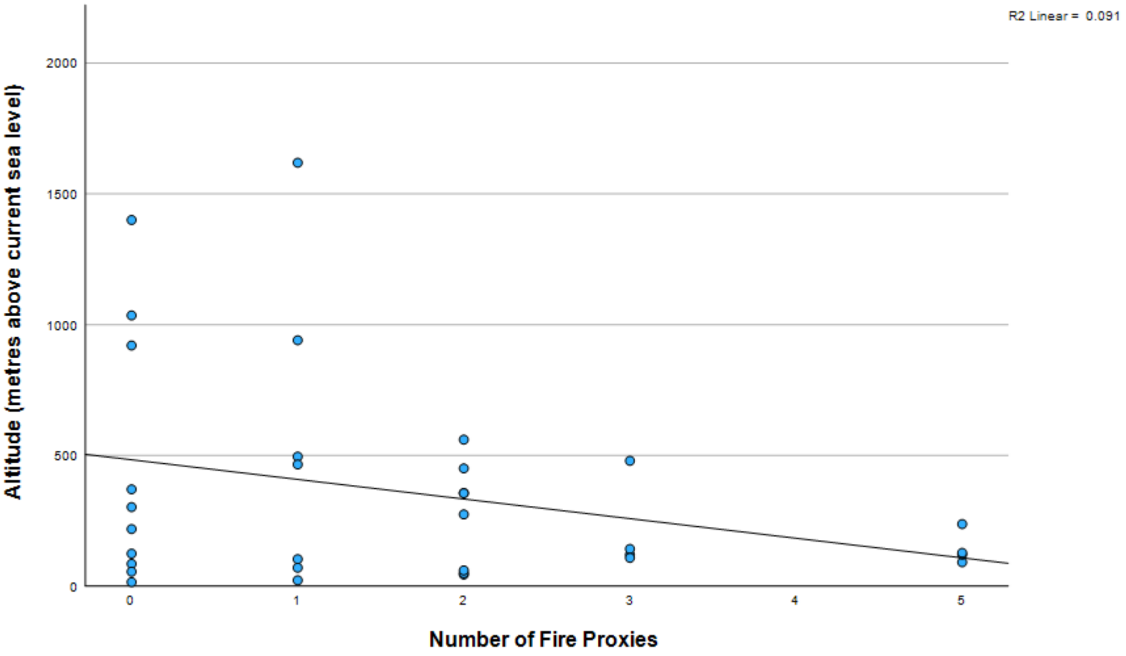


Graph A24: A graph showing the lack of correlation between wood-to-charcoal conversion rates and duration of combustion; slower-burning woods may in theory create more charcoal, but this does not appear to be the case (R2 = 0.023).

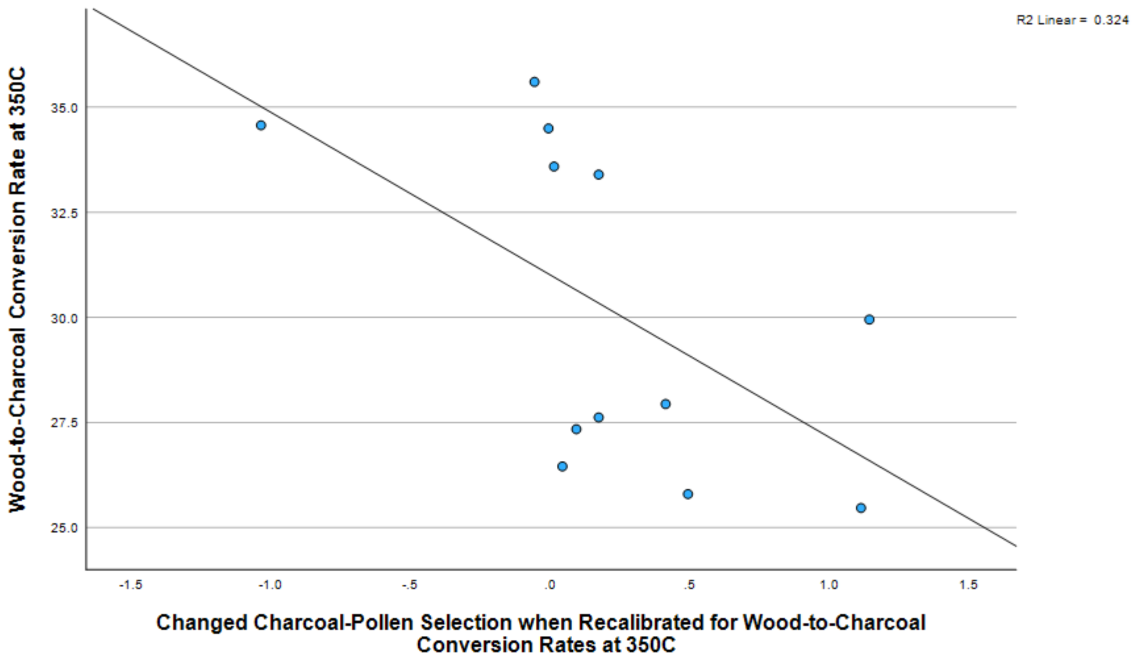
Graph A25: A comparison of the first date of investigation of Middle Palaeolithic cave and open-air sites, and how many fire proxies have been found in each. The R2 value is very low (0.01); the suggestion is that sites excavated longer ago tend to show more fire evidence, possibly because more important sites were excavated longer ago, and more ephemeral sites are being found today.



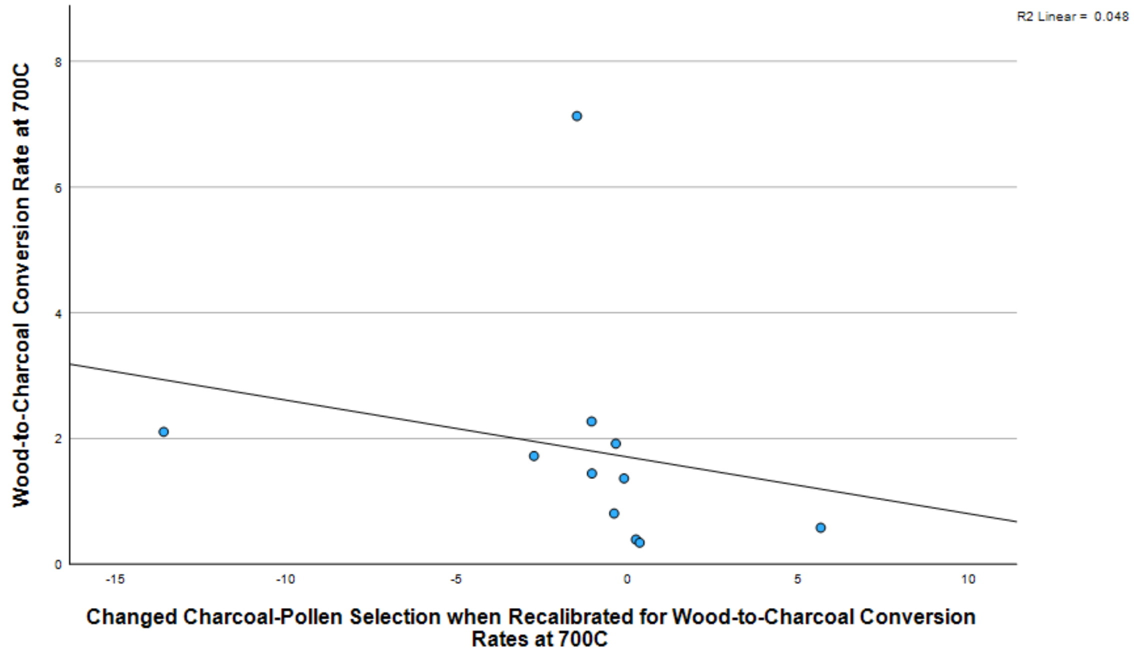
Graph A26: A comparison of how the number of fire proxies found in Middle Palaeolithic cave sites varies with altitude. As expected, fewer proxies (and therefore probably less fire) occurred at higher altitudes, where it may be a product of a lack of firewood (R2 = 0.075).



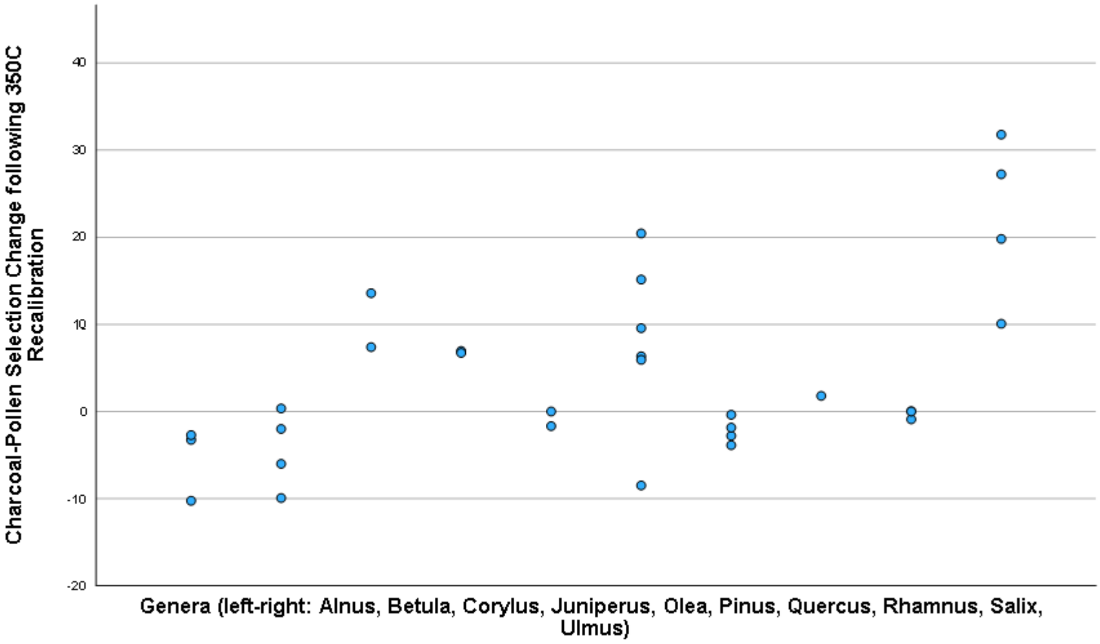
Graph A27: A similar comparison of fire proxies with altitude, for Middle Palaeolithic open-air sites. As with Graph A26 for cave sites, there is a similar increase of fire in lower-altitude sites (R2 = 0.091).



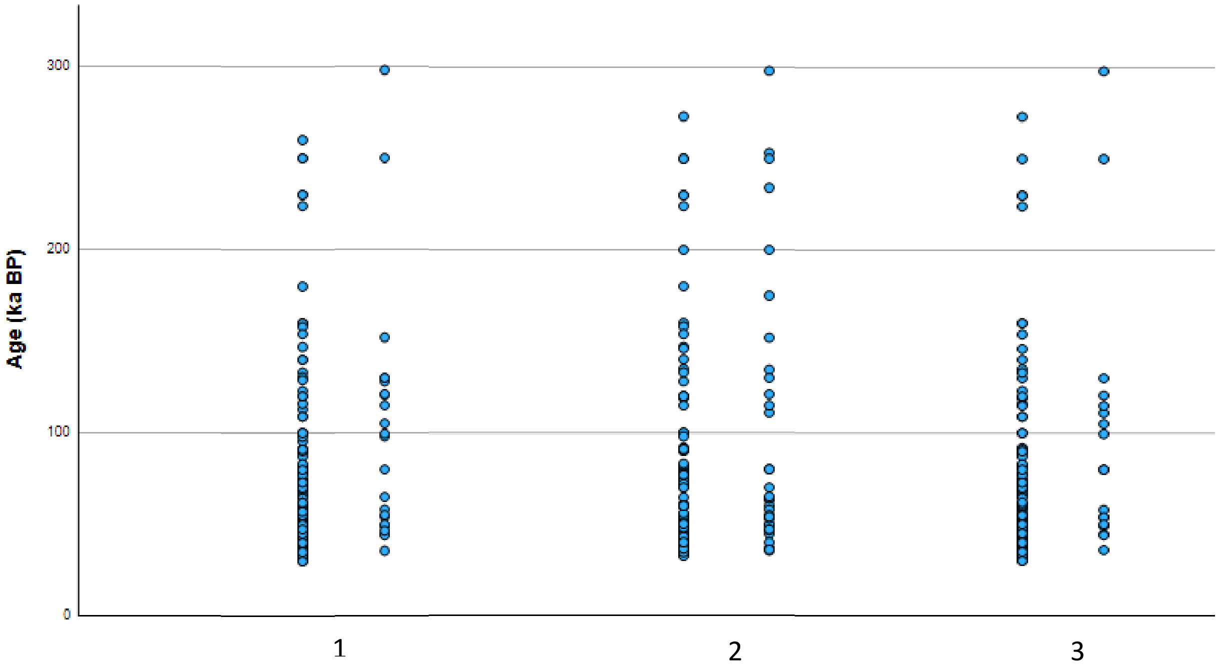
Graph A28: A comparison between wood-to-charcoal rates at 350C, and how much charcoal-pollen selections change when recalibration is undertaken on the charcoal. Although the R2 linear is stronger than many in this these (0.324), with woods with high wood-to-charcoal conversion rates correspondingly having a lowered charcoal-pollen selection when recalibrated, it is of course weakened by some selections including pollen and no charcoal, and thus nothing changing compared to the base values on recalibrating it.



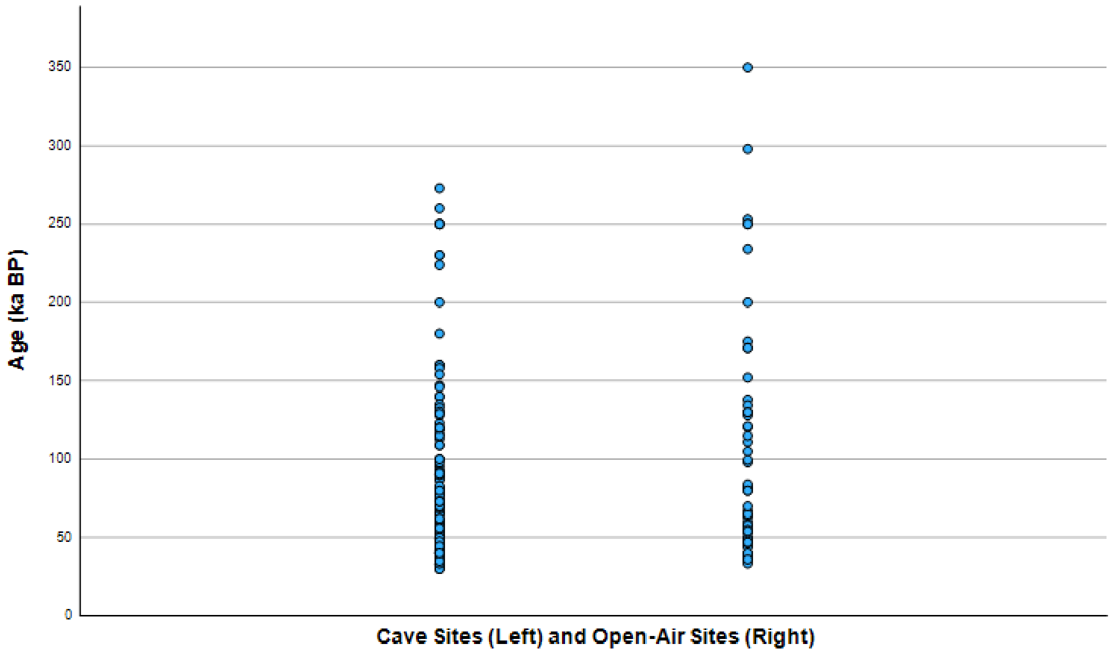
Graph A29: An identical graph to Graph A28, but calculated for conversion rates and recalibrations at 700C. Likewise, a negative correlation is seen, however this is significantly weaker (R2 = 0.048) than that for Graph A28.



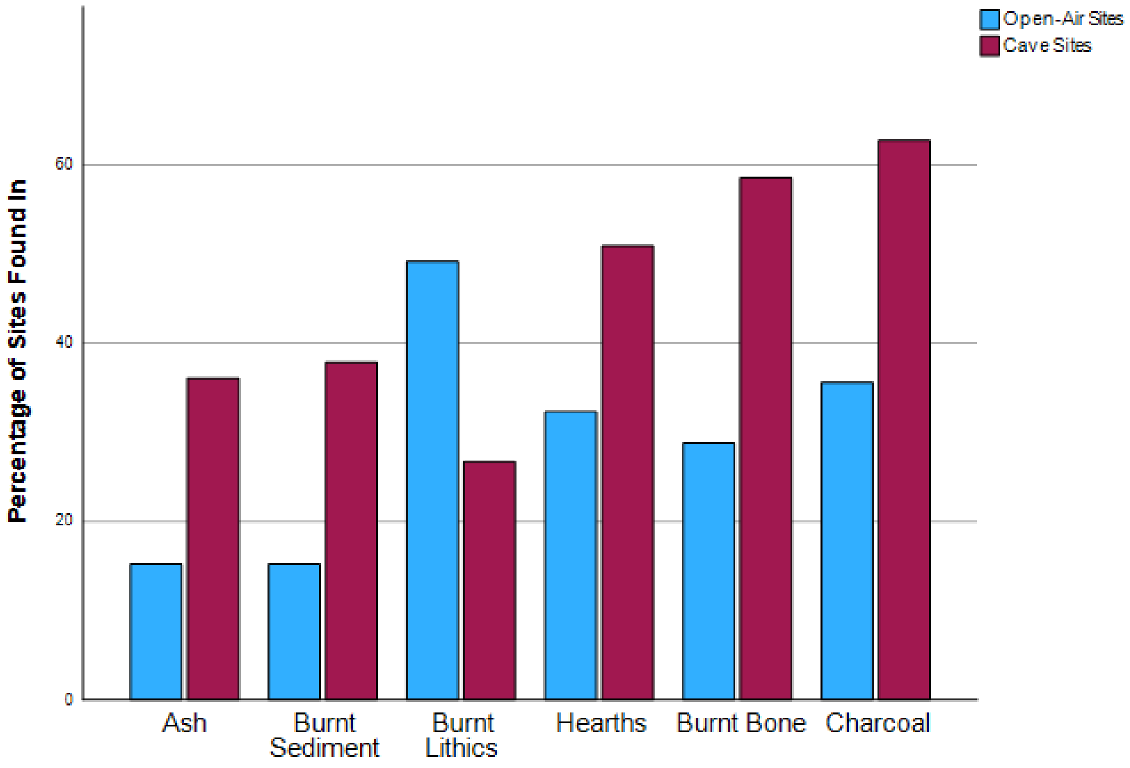
Graph A30: A graph demonstrating how various genera's charcoal-pollen selection changes following recalibration for 350C. A positive value in the Y-axis means that pollen-charcoal discrepancies have increased, and a negative one means that they have decreased (possibly suggesting that charcoal or pollen production biases were responsible for the discrepancy). The positive selection change is much more than the negative one, suggesting that pollen and charcoal production biases were not the primary cause of these charcoal-pollen discrepancies.



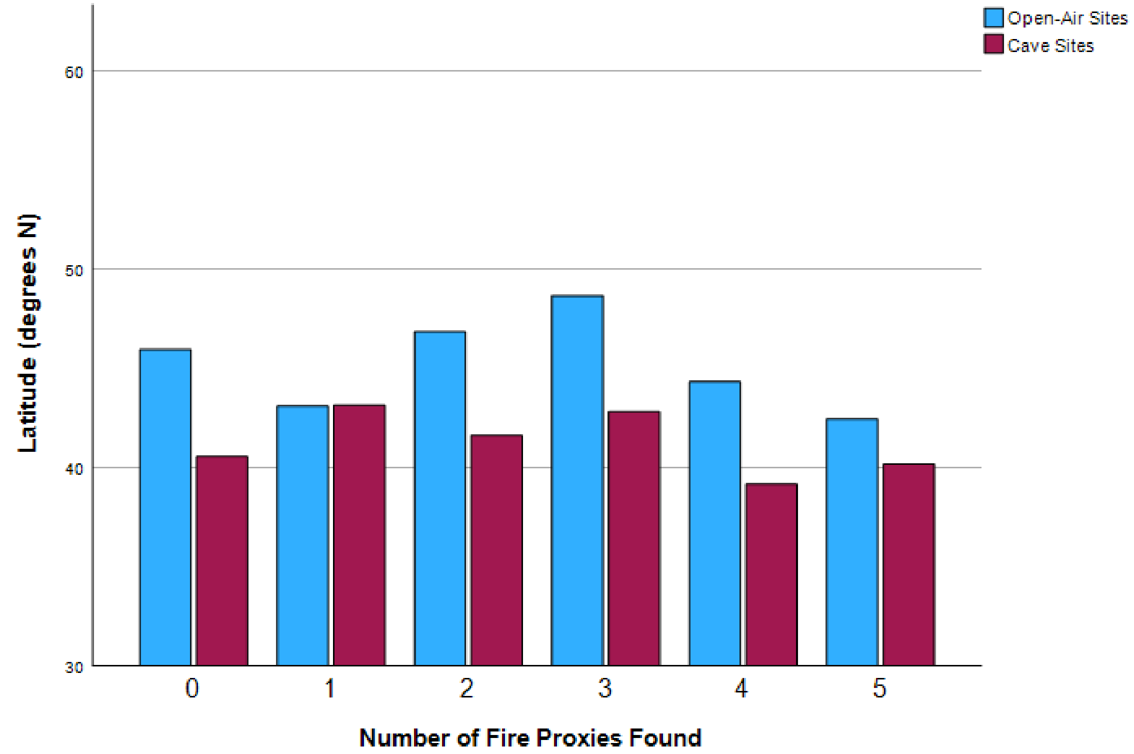
Graph A31: A graph showing the ages of cave ond open-air sites containing (1) charcoal, (2) burnt lithics and (3) hearths. Within each set, the right-hand column represents cave sites and the left-hand column represents open-air sites. Although each site type has a wide spread of dates, open-air sites tend to be older.



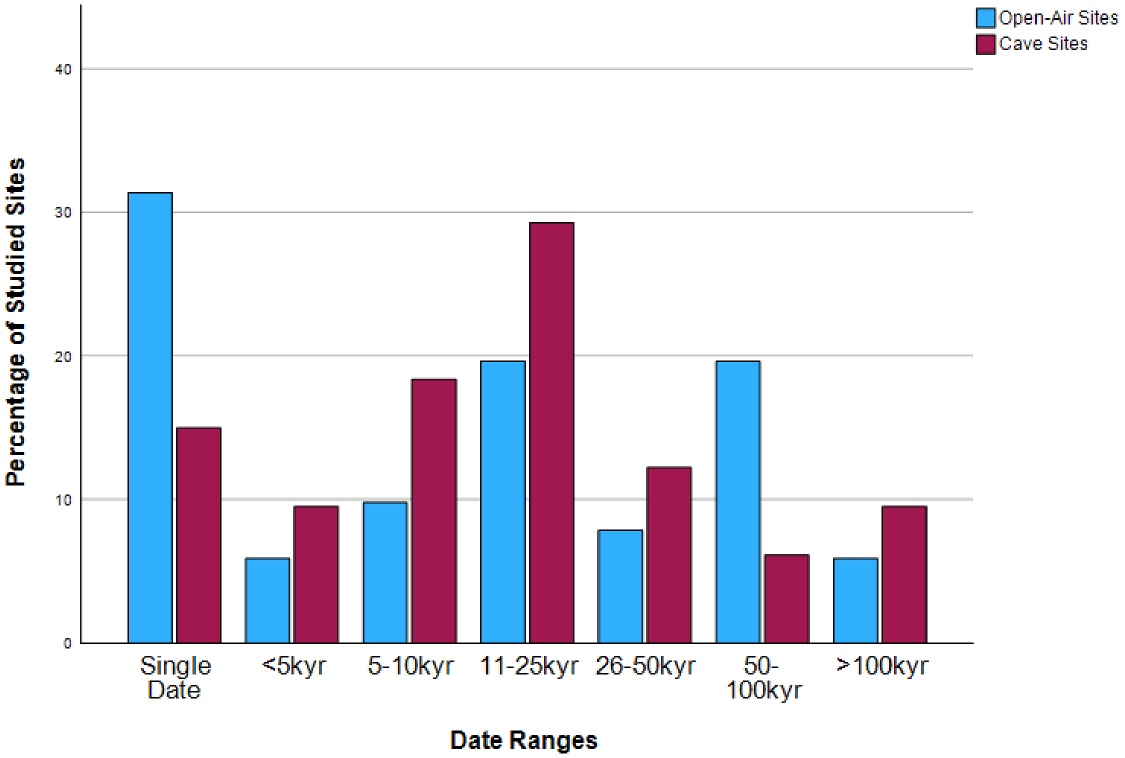
Graph A32: A comparison of the ages of cave and open-air sites. Although both have a wide spread, cave sites tend to be younger on average.



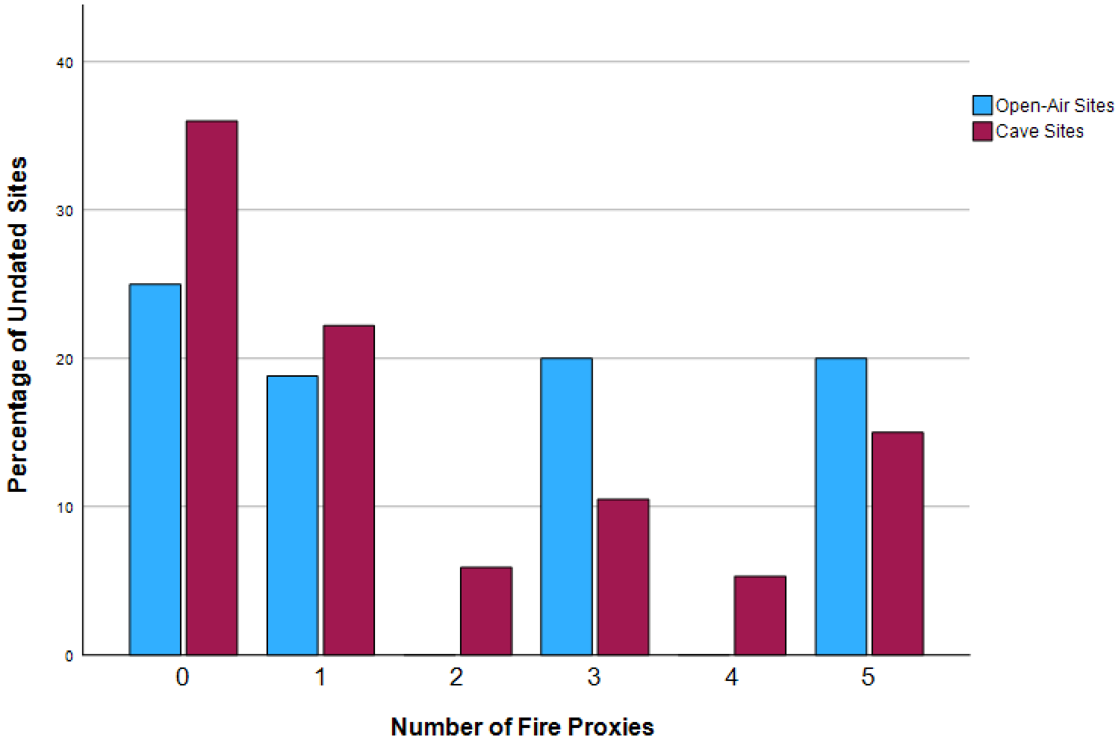
Graph A33: A comparison of the various fire proxies in cave and open-air sites. All are almost twice as common in caves as open-air sites, except for burnt lithics where the trend is reversed. This Graph corresponds with Table 3.8, p.87.



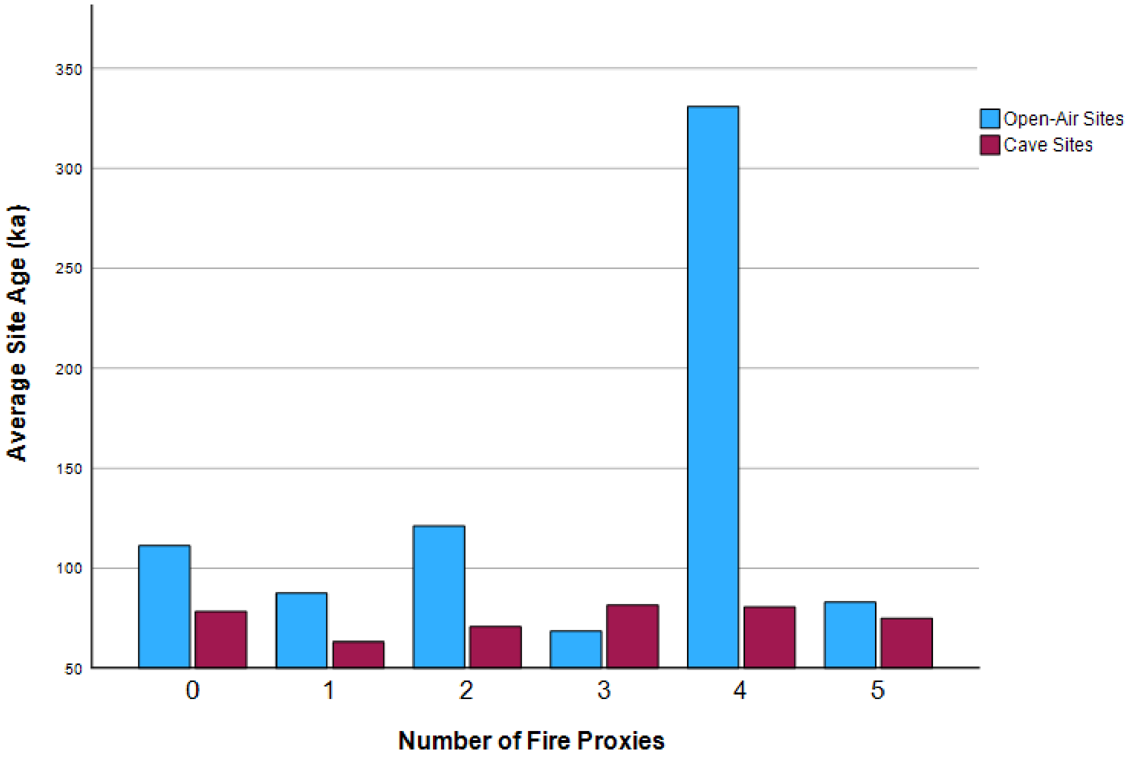
Graph A34: A comparison of the number of fire proxies found in cave and open-air sites with their latitudes. The latitudes included are the ones where Neanderthal sites have been found, from c.30N (the Levant) to c.60N (Finland). Open-air sites tend to be further north on average, regardless of how many proxies are found there. This Graph corresponds to Table 3.9, p.92.



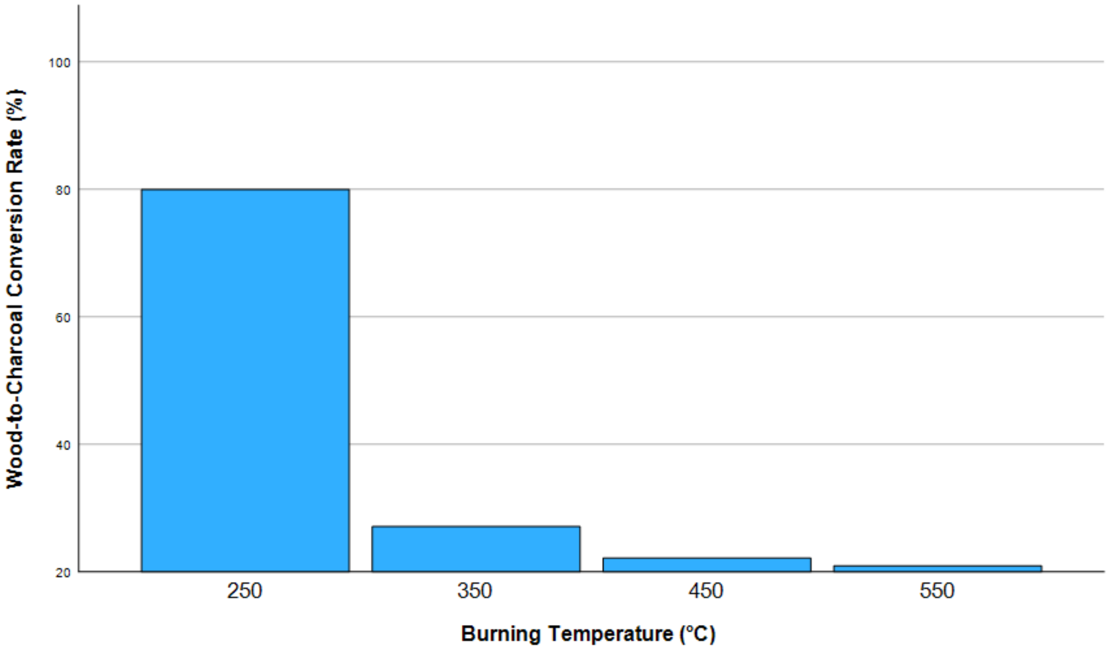
Graph A35: A comparison of the spread of dates for cave and open-air sites, representing either shorter or longer occupation series, or more or less accurate date ranges. Open-air sites are much more likely to have only single dates available for them, and cave sites are most likely to represent c.11-25kyr of occupation. This Graph corresponds to Table 3.11, p.99.



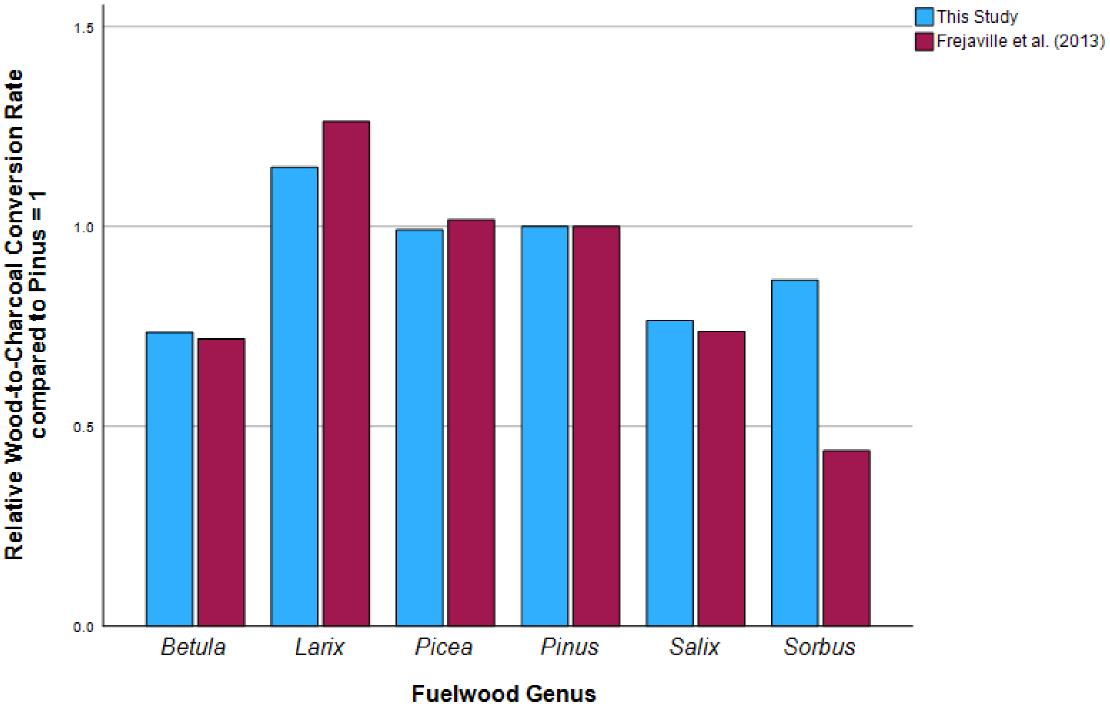
Graph A36: A comparison of the number of fire proxies in undated caves and open-air sites. Undated caves tend to have fewer proxies than open-air sites, suggesting that cave sites may depend on the fire proxies themselves as dating materials (charcoal for radiocarbon dating, burnt lithics for TL etc.) more than open-air sites. This Graph corresponds to Table 3.12, p.99.



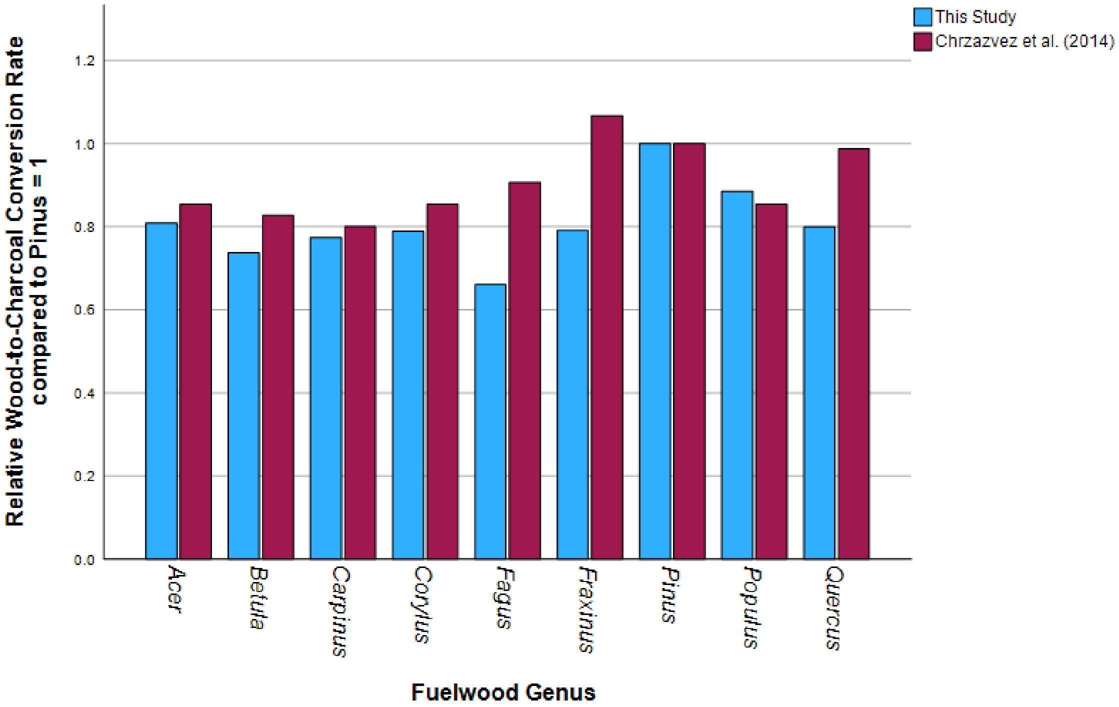
Graph A37: A comparison of the average ages of caves and open-air sites, and the number of fire proxies in each site. Open-air sites are older in almost all instances; this is particularly noticeable in sites with 4 different fire proxies. However, open-air sites had few examples of sites with 4 different proxies, skewing the results towards the few (very old) examples. This Graph corresponds to Table 3.14, p.101.



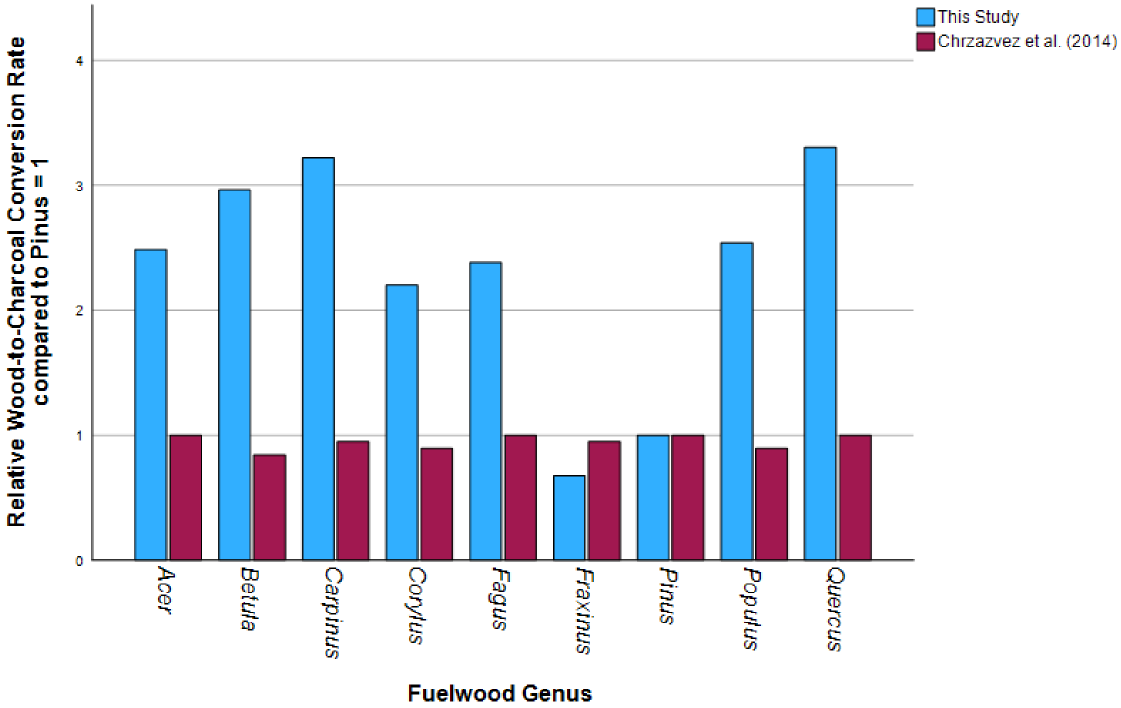
Graph A38: Various wood-to-charcoal conversion rates when Malus wood was experimentally burnt at different temperatures. Although increasing temperatures consistently reduced charcoal yields, the largest difference by far was between 250C and 350C, suggesting that this is the key temperature for full charcoalification. This corresponds to Table 6.3, p.172.



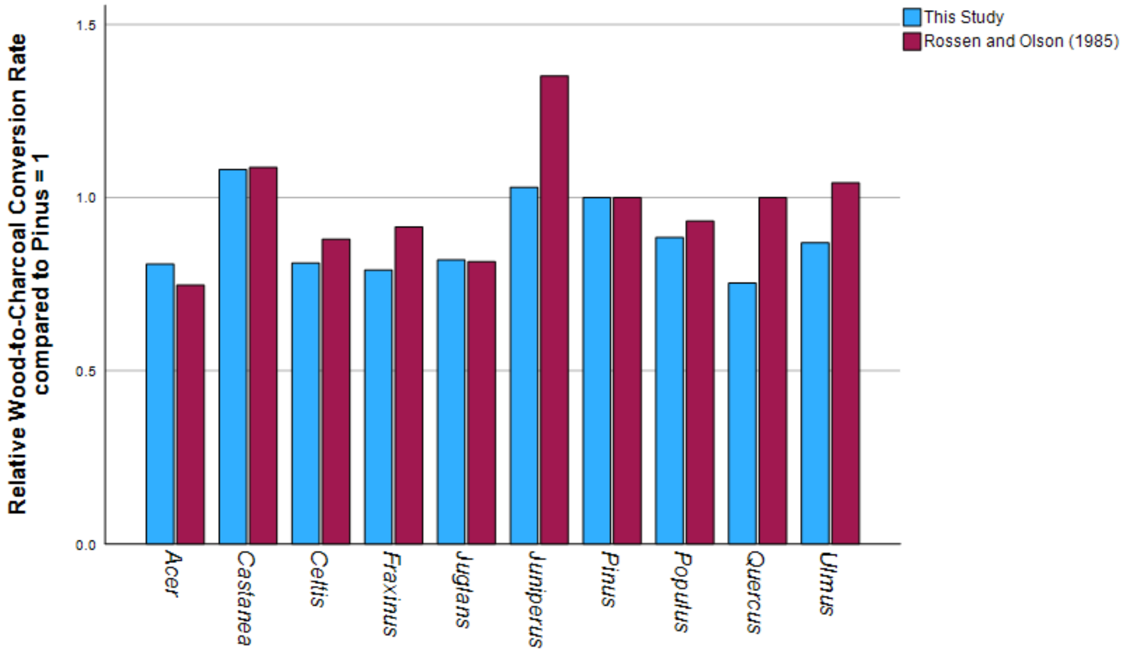
Graph A39: A comparison of my study with the results from Frejaville et al. (2013). This is the most similar of the studies to mine, and all the tested genera show very similar conversion values to my values, with the exception of Sorbus. This Graph corresponds to Table 7.4, p.181.



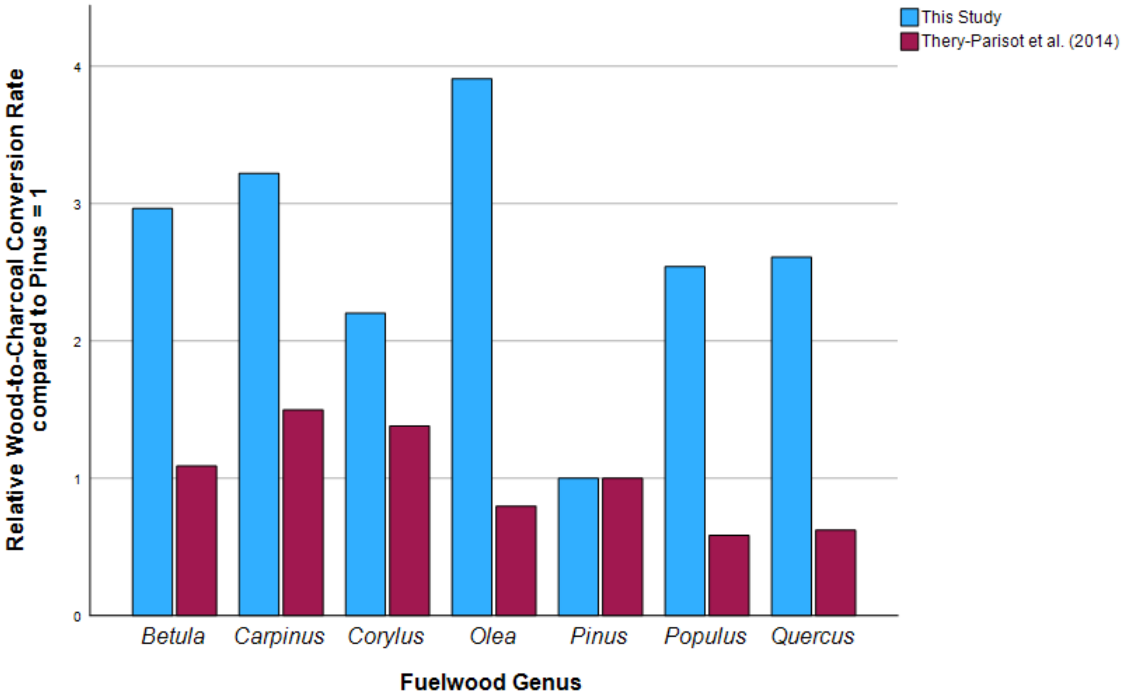
Graph A40: A comparison of my study with the results from Chrzazvez et al. (2014). Although some values are similar, this is more dissimilar than mine and Frejaville et al.'s (2013) study; particularly for Fagus and Fraxinus. This Graph corresponds with Table 7.5, p.182.



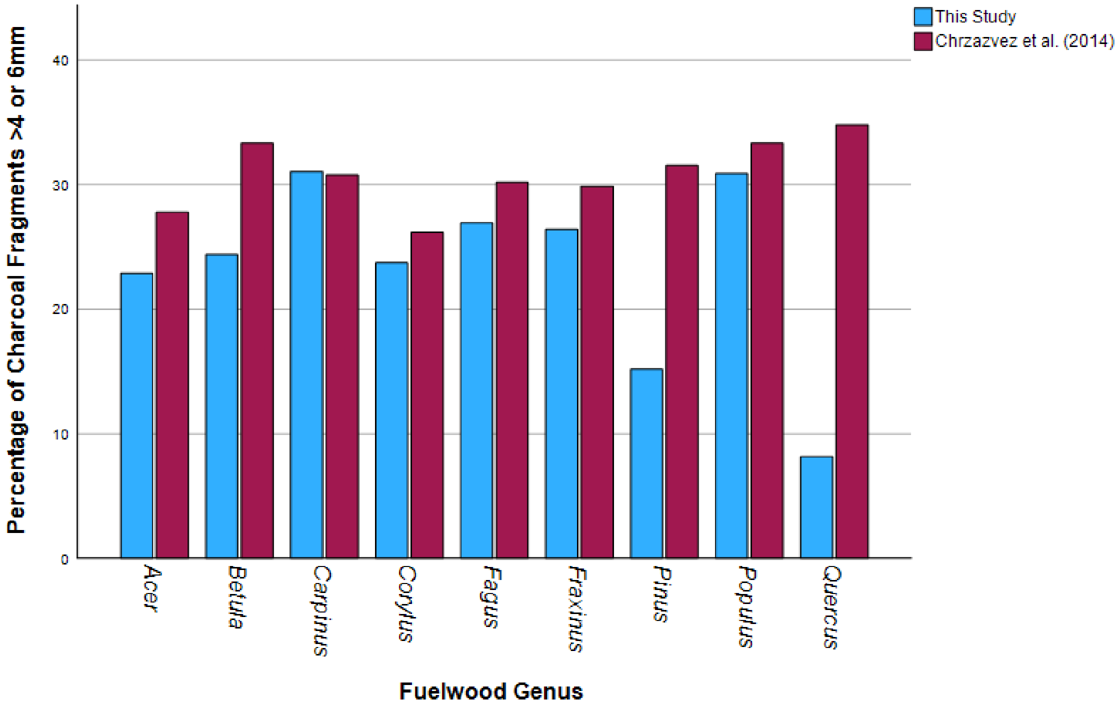
Graph A41: A comparison of my higher-burning values (700C) with the higher-burning values of Chrzazvez et al. (2014). The values are very disparate, with myself almost always finding much higher conversion rates than Chrzazvez. This Graph corresponds with Table 7.6, p.183.



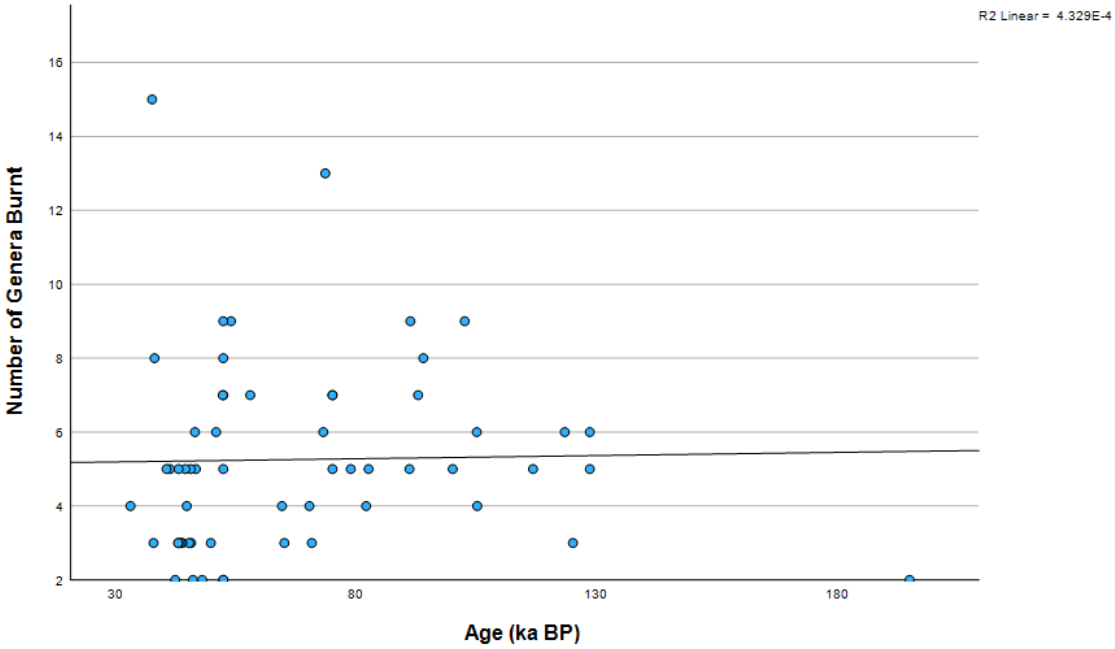
Graph A42: A comparison of my study with the results of Rossen and Olson (1985). Although some genera such as Acer, Celtis and Populus present similar values, others such as Juniperus and Quercus are much more disparate. This Graph corresponds with Table 7.8, p.184.



Graph A43: A comparison of my study with the results of Thery-Parisot et al. (2014). All the results are extremely disparate between our two studies; Pinus only has identical values because everything is based around an arbitrary Pinus = 1 value. Otherwise, my fuelwoods consistently create more charcoal in proportion to Pinus = 1. This Graph corresponds to Table 7.9, p.185.



Graph A44: A comparison between my results and those of Chrzazvez et al. (2014). Although some values are similar, many are disparate, especially Pinus and Quercus. This is most likely the result of Chzazvez' sieving size being 4mm and mine being 6mm, and this difference being sufficient to account for the difference in values seen here. This Graph corresponds to Table 7.18, p.204.



Graph A45: A comparison of the age of sites and the number of genera burnt there. Although more recent sites are the only ones with over 10 genera burnt, there is no statistically-significant trend over time, and the regression line is virtually flat (R2 = 4.329e-4). This Graph corresponds to Table 8.36, p.239-241.

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