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Aboriginal fire use: from responsible for Australia's environmental change to a successful tool for the management of natural fires

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RESUMEN

La adquisición del fuego es uno de los aspectos clave del proceso de hominización que hizo posible la expansión del nicho ecológico en los primeros homininos. Aunque no hay consenso sobre el momento preciso en que los homininos adquirieron el control del fuego, no hay duda de que permitió la transformación gradual de los paisajes. Durante el Pleistoceno tardío, se produjo un evento de extinción global de la megafauna en varias regiones de la Tierra, incluida Australia. Este proceso fue sincrónico con la llegada del *Homo sapiens* a Norteamérica y Australia, por lo que se ha planteado la hipótesis de que la influencia humana habría sido determinante en la desaparición de la megafauna. En el caso concreto de Australia, el particular uso del fuego por parte de los aborígenes, denominado "fire-stick farming", que proporciona un mecanismo para aumentar la productividad mediante la quema selectiva de parches de vegetación madura, sería el factor desencadenante que desencadenaría la extinción de la megafauna. Sin embargo, no está claro que el "fire-stick farming" fuera tan determinante, y algunos autores abogan por un proceso impulsado por el clima. Sea como fuere, la práctica tradicional australiana de quemas se ha convertido ahora en una herramienta útil para el control de incendios forestales y un mecanismo para aumentar la biodiversidad en los paisajes australianos.

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ABSTRACT

The acquisition of fire is one of the key aspects of the process of hominization that made possible the expansion of the ecological niche in the early hominins. Although there is no consensus on the precise timing that hominins acquired the control of fire, there is no doubt that it allowed the gradual transformation of landscapes. During Late Pleistocene, a global extinction event of the megafauna is reported in several regions of the Earth, including Australia. This process was synchronous with the arrival of *Homo sapiens* in North America and Australia, the reason for which it has been hypothesized that human influence would have been determinant in the disappearance of the megafauna. In the specific case of Australia, the particular use of fire by Aboriginals, called fire-stick farming, which provides a mechanism to increase productivity by selectively burning patches of mature vegetation, would be the trigging factor that unleashed megafaunal extinction. However, it is not clear that fire-stick farming was so determinant and some authors advocate for a climate-driven process. Be that as it may, traditional Australian burning practice has now become a useful tool for wildfire control and a mechanism to increase biodiversity in Australian landscapes.

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Introduction

The capacity to manipulate fire has traditionally been described as a relevant milestone in hominin evolution that was favoured by the selective advantages it offered and that had a marked impact on the evolution of both biological and social traits (Pyne, 1994; Wrangham and Carmody, 2010). Among the advantages, the exploitation of new ecological niches by hominin populations is one of the most relevant, both in the physical dimension (*i.e.*, occupying new areas, regions... or habitats not previously occupied) and temporal (*i.e.*, being able to maintain activity in periods of the day that they couldn't before). In this sense, campfires provided both light and heat, allowing for increased safety from predators (Pyne, 1994; Gowlett and Wrangham, 2013; Attwell, Kovarovic and Kendall, 2015; Gowlett, 2016). This lengthening of 'daylight' (Attwell, Kovarovic and Kendall, 2015) had a marked effect on photoperiodicity and even affected melatonin production by altering the biological clock and sleep patterns and the timing of puberty (Burton, 2009; Attwell, Kovarovic and Kendall, 2015). Apart from the influence on biological features, the acquisition of fire would also have triggered the development of new social traits, such as tool tempering, the improving of flaking properties, the extension of the activity time, and the beginning of cooking and preserving food (Bellomo, 1994; Brown et al., 2009; Attwell, Kovarovic and Kendall, 2015; Henry, 2017). Consequently, fire would represent a selective advantage for hominins (Twomey, 2013; Dunbar and Gowlett, 2014), so its acquisition would be unequivocally favoured to the point it would be indispensable for the hominins since fire-induced calories became central for their survival (Wrangham and Conklin-Brittain, 2003; Barkai et al., 2017). However, the benefits of fire acquisition may vary among environments and habitats (Henry, Büzel and Bazin, 2018). Associated costs to fuel collection can be high in less-forested environments and even exceed the benefits (Henry, Büzel and Bazin, 2018). Thus, the acquisition of fire by hominins was unlikely universal and homogeneous, but that it depended on the particular environmental conditions of each hominin population and in which both costs and benefits were balanced (Henry, Büzel and Bazin, 2018).

In this sense, although the earliest evidence of occasional and opportunistic use of fire may be tracked back until more than a million years ago in the African continent (Brain, 1993; Beaumont, 2011; Berna et al., 2012; Pickering, 2012; Hlubik et al., 2019); unequivocal evidence for the early use of fire dates back to the beginning of the Middle Paleolithic, circa 250-400kya in the Levant (Karkans et al., 2007; Berna and Goldberg, 2008; Shimelmitz et al., 2014), Europe (Gowlett, 2006; Fluck, 2007; Roebroeks and Villa, 2011) and China (Weiner et al., 1998; Zhong et al., 2014) (Table 1). However, several articles states that unequivocal use of fire can be extended to ~800kya at the Isreali site of GesherYa'akov (~790kya, Jordan Valley) (Goren-Inbar et al., 2004), the Spanish site of Cueva Negra del Estrecho del Río Quipar (Walker et al., 2013) and the Chinese site of Zhoukoudian (Zhong

Table 1. Some of the putative earliest evidence of fire use by hominins.

Site	Country	Date (Mya)	Evidence of fire	Reference
Koobi Fora	Kenya	1.6	Burnt clay patches	Rowlett (2000)
Swartkrans	South Africa	1.6	Burnt bones	Brain (1993)
Gadeb	Ethiopia	1.5	Burnt rocks	Barbetti (1986)
Chesowanja	Kenya	1.4	Burnt clay patches	Gowlett et al. (1981)
Wonderwerk Cave	South Africa	1.0	Burnt sediments	Beaumont (2011); Berna et al. (2012)
Gesher Benot Ya'aqov	Israel	0.79	Burnt wood and flints	Alperson-Afil (2008)
Zhoukoudian	China	0.78	Mammal bones and burnt hackberry shells, lithic and eggshell flakes	Zhong et al. (2014); Gao et al. (2017)
Schöningen	Germany	0.4	Burnt wooden implements	Roebroeks and Villa (2011); Stahlschmidtet al. (2015)
Qesem Cave	Israel	0.3	Wood ash and burnt animals	Barkaiet al. (2017)

et al., 2014; Gao et al., 2017). From that moment on, its intentional use became generalized. Neanderthal use of fire is well documented both in Europe (Sandgathe et al., 2011; Aldeias et al., 2012; Goldberg et al., 2012; Vallverdú et al.,2012; Pop et al., 2016) and in the Levant (Albert, Berna and Golberg, 2012), although some authors deny that use of fire was an essential aspect of *Homo neanderhtalensis*' behavior, at least in Western Europe (Sandgathe et al., 2011). Fire is well documented in Near East during the Middle and Upper Paleolithic (Goldebrg, 2003; Blascoet al., 2016).

The review aims to specifically analyse the use of fire by Australian Aborigines hunter-gatherers. Precisely, this group of hunter-gatherers presents a set of biological adaptations to the cold such as insulative cold adaptation (*i.e.*, lower skin temperature when exposed to cold with unchanged metabolic rates and core temperatures) and insulative hypothermic adaptation (Daanen and Van MarkenLichtbenbelt, 2016; Yurkevicius et al., 2020). Australian aborigines do not use clothes (Young, 1996), although more recent systematic analyses have identified a clear trend of decreasing "no clothes" reports with increasing latitude (Gilligan, 2008). In any case, although there are some reports that when they slept they had a small campfire, the emphasis on coping with the cold has always been on their biological adaptations: they slept directly naked overnight on the bare ground allowing the temperatures of their feet to drop to 12-15ºC (Scholander, 1958; Hammel, 1959; Young, 1996). It seems, then, that particularly in this group, fire did not have a particularly prominent function in fighting the cold, one of the main arguments traditionally argued for the acquisition of fire by humans. In any case, the Australian Aborigines do make extensive use of fire, framed within practices of transforming the landscape to increase its productivity. Therefore, the colonization of the Sahul paleocontinent by the Australian Aborigines, in a context in which the demise of the megafauna is observed, may provide information about the use of fire by these (and other) populations.

The colonization of Sahul

The Sahul paleocontinent represents a vast region that was never inhabited by *Homo sapiens* due to the existence of the Wallace Line. Its recent colonization may allow us to broaden our knowledge on territory occupation, habitat exploitation, and the creation of ecological niches and the transformation of landscapes due to cultural practices. Archaeological evidence of Australia's human occupation often yields heterogeneous dates, especially depending on the region in which the site is located, so the southernmost sites tend to have later occupation dates. The oldest human remains place Australia's colonization of about 40kya (Bowler et al., 2003; Olley et al., 2006), although archaeological evidence of artefacts buried, delay its colonization until 45-60kya (Roberts et al., 1994; Turney et al., 2001a,b; Bird, Hope and Taylor, 2004; David et al., 2011; Clarkson et al., 2015). Nevertheless, recent reviews of the archaeological record conclude that *Homo sapiens* colonized Sahul at least 45-47kya (Bird et al., 2013; O'Donell et al., 2015; Wood et al., 2016), although northern territory, which was the entrance gate to Australia, could have been colonized quite earlier, around 50-60kya (Roberts et al., 1994; Clarkson et al., 2015; Saltré et al., 2016). Genetic studies coincide with the archaeological record. Recent studies of the mtDNA of Aboriginal Australians suggest that the estimated ages of the indigenous haplogroups range from 39- 55kya (Nagle et al., 2016a,b). This colonization of Australia was done by the preferential occupation and exploitation of savannah-woodlands habitats of the continental interior (Bird, Hope and Taylor, 2004), which were favoured by periodically wetter conditions that affected Australia's continental interior between 40-60kya (Kershaw and Nanson, 1993; Magee and Miller, 1998; Johnson et al., 1999; Miller et al., 1999), occupying the arid southern interior by 40-49Ka (Bird, Hope and Taylor, 2004; Hamm et al., 2016).

Australia's megafauna extinction

During the Late Pleistocene, a global extinction event of the megafauna affected several regions of the Earth, although in each region human impact and environmental factors –climate change and the subsidiary climatically driven nitrogen sink- were uneven (Barnosky et al., 2004; Varela et al., 2010; Faith, 2011; Iwase et al., 2012; Turvey et al., 2013;

Flores, 2014; Sandom et al., 2014; Cooper et al., 2015). In the particular case of the paleocontinent Sahul, this megafaunal extinction process is a challenging problem and consensus has not yet been reached on whether this process was "climate-driven" or "human-driven" (Saltré et al., 2016). Although this extinction process is commonly referred to as the "megafaunal extinction event", actually not only large species became extinct, but a wide range of terrestrial animals of a variety of sizes (Flannery, 1990). Anyway, this megafaunal extinction supposed the loss of most terrestrial mammals exceeding 10kg in adult, reptiles exceeding 50kg in adult body weight and flightless birds, resulting in the extinction of about 50 large vertebrate's species (Flannery, 1990). Up to 23 out of 24 genera of large and medium-sized land animals weighing more than 45kg became extinct in the Late Pleistocene (Roberts et al., 2001). This megafaunal extinction event occurred circa 44-46kya (Miller et al., 1999; Roberts et al., 2001; Pate et al., 2002; Gillespie, Brook and Baynes, 2006) in synchrony with the first arrival of *Homo sapiens* to Australia, the reason why a large number of researchers tend to directly associate both events (Flannery, 1990; Miller et al., 1999, 2005; Roberts et al., 2001; Johnson, 2005; Gillespie, Brook and Baynes, 2006; Brook et al., 2007; Rule et al., 2012; Saltré et al., 2016). The "human-driven" hypothesis contemplates that the extinction of large-sized occurred either by their direct overhunting during sustained periods (Brooks and Bowman, 2004; Miller et al., 2005; Brook and Johnson, 2006; Gillaspie et al., 2006; Brook et al., 2007), a rapid overkill of the megafauna some authors have called "blitzkrieg" (Brook and Bowman, 2004), or by ecological disturbances and disrupted trophic dynamics caused natural fire regimes alteration due to "fire-sticking" farming practices, as detailed below (Pickup, 1998; Miller et al., 2005). In this sense, an increase in fire activity around 45kya in several sites has been interpreted by some authors as a corroboration proof of the "human-driven" hypothesis (Turney et al., 2001b).

Anthropogenic use of fire by hunter-gatherers

Hunter-gatherers' activity alters ecosystems either unintentionally or deliberately, as is the case of fire-sticking farming (Thompson, Wright and Ivory, 2020). Hunter-gatherer populations that show a strategy favouring the exploitation of delayed-return resources (*i.e.,* land management practices through the manipulation of plant life at levels less intensive than in agricultural societies) may have a negative impact on the environment and biodiversity similar to that of agricultural populations as a result of a reduction in mobility combined with a population increase (Feeney, 2019). This land management can include a wide variety of practices as burning, coppicing, pruning, weeding, thinning, clearing, transplanting, replanting of propagules, sowing and planting seeds, as well as land manipulations techniques as diverting streams for irrigation, digging, tilling and fertilizing (Anderson, 2005; Deur and Turner, 2005). The construction of physical structures to drive the game by hunter-gatherers is also landscape modification designed to increase the yield and predictability of natural resources (Lemke, 2021). In this sense, immediate-return hunting and gathering, which involved little or no land management, was the human lifeway most closely approaching ecological sustainability (Feeney, 2019). Traditionally, fire represented a key point to ecosystem management intended to increase prey abundance and production of desirable wild plants and annual resources in specific locations (Gouldblo, 1992; Pyne, 2005; Smith, 2011). This cultural practice of burning is an intentional process of "niche construction" (Bird et al., 2008; Smith, 2011; Rambo, 2014; Thompson, Wright and Ivory, 2020; Lemke, 2021) that acts by modifying landscapes into smaller patches and altering vegetation communities, enhancing biodiversity (Bird et al., 2008).

This use of fire to increase the productivity of an ecosystem is most common among hunter-gatherers from dry regions, like deserts, savannahs and seasonally dry forests (Rambo, 2014), although some studies have highlighted that it has also been used in temperate and wet ecosystems, as is the case of Canadian boreal forests (Lewis and Ferguson, 1988) and even humid Malaysian rainforest (Rambo, 1985). In this sense, a cross-cultural study of 96 different groups of hunter-gatherers showed that almost half of them (51) did not burn (that corresponded to groups that inhabited areas with high rainfall or at high latitudes), whereas the other half of the groups, *i.e.*, 45, regularly involved fire in their cultural strategies related to food acquisition (Keeley, 1995). However, it is interesting to distinguish between those groups that used fire for hunting (16 out of 45) from those that used it to promote ecological succession and increase the productivity of the ecosystem (29 of 45) (Keeley, 1995). The use of frequent burning of savannah vegetation by hunter-gatherers has the intention to increase both the quantity and quality of tender shoots and leaves of forage plants that regenerate after the fire (Rambo, 2014). Studies carried out in North America and Europe have shown that careful use of fire can increase the carrying capacity of the environment for grazing animals by 300% to 700% over that of unmanaged ecosystems (Mellars, 1976). Studies of areas burned by Aboriginal Australians have also found increases in the population of desired game species and edible wild plants (Murphy and Bowman, 2007; Bird et al., 2008; Vigilante et al., 2009).

Fire-stick farming: a niche construction process

Fire-stick farming refers to Australian Aborigines' traditional cultural practice of periodically landscapes burning with frequent and low-intensity fires to directionally modify it in a way that increases the availability of nutrients, resources and return rates in low-diversity landscapes (Jones, 1969). Australian Aborigines periodically burn small areas or patches covered by mature spinifex vegetation to restart the ecological succession, as well as eliminating this climax vegetation and, consequently, increasing nutrient availability, enhancing the productivity of herbaceous plants, and, therefore, the global habitat (Bird et al., 2008). Through this practice, a highly mosaic landscape is achieved, with areas at a different moment of the ecological succession, favouring habitat-generalist species with intermediate dispersal ranges, as well as promoting the re-colonisation of burnt habitats by more specialist species with smaller dispersal ranges from those areas that had not been burnt (Bird et al., 2008). This dynamic of constant regeneration of ecological successions causes a substantial increase in biodiversity and, consequently, the foraging efficiency of aboriginal hunter-gatherer populations. Bird et al. (2008) tested the fire-sticking farming hypothesis and showed that the burning of areas of mature spinifex increased return rates in low-diversity landscapes, but these benefits decreased inversely proportional to diversity. It means that the burning practice is a favourable strategy only in environments with low diversity, which can be increased rapidly by selective burning of mature vegetation patches. By controlling the time of the year and the frequency a region was regularly burned, Australian Aboriginals promoted an increase in the yield of wild plants that were regularly consumed or that were directly predated by wild animals that are frequently hunted and, consequently, of the density of those species they preferred to hunt (Rambo, 2014). This landscape transformation using fire represents deliberate colonization of nature not qualitatively different from that practised by agricultural societies and enabled Australian Aborigines to modify the ecosystem in a certain direction to self-build a particular ecological niche (Rambo, 2014; Smith, 2015).

Anthropogenic fire and the demise of Australian megafauna

Australian ecosystems were particularly susceptible to fire due to nutrient-depletion of most soils (Orians and Milewski, 2007): the “Nutrient-Poverty/intense-Fire Theory” predicts that plants growing in environments with abundant sunlight and adequate water availability, but on poor-nutrients soils synthesize an excess of carbohydrates that cannot be combined with or catabolized by nutrients (calcium, phosphorus, zincs…) for metabolism and are allocated to the production of nutrient-rich foliage and reproductive tissues (Orians and Mileski, 2007). Precisely, the accumulation of this high large amount of biomass and its combination with low rates of herbivorism (since in such environments plants tend to develop defences against it), provides fuel for the occurrence of high-intensity fire (Orians and Mileski, 2007). Therefore, periodically occurrence of wildfire in Australia is intrinsic and consubstantial to the existence of poor soils and has played a prominent control of Australian vegetation throughout the Quaternary and Holocene (Black and Mooney, 2006): late dry season burns (September to December) were the normal fire pattern in Australia (Stott, 2000). However, the burning practices of the earliest Australian Aboriginals differed enough from that of the natural fire cycle to disrupt ecosystems across the semiarid zone (Miller et al., 1999). In addition to this, nutrient-poor soils also partly constrain woody cover in Australia (Mills et al., 2013). In mesic savannahs, the main obstacle to maintaining the population of trees is the regeneration of new plants, with tree cover being limited by fire, which acts as a demographic bottleneck by reducing the establishment of seedlings and preventing saplings (Bond and Keeley, 2005). In this scenario, although the introduction of fire-stick farming initially favoured Australian Aboriginals by increasing short-term outcomes, it had a deep long-term impact on ecosystems (Bowman, 1998) with a drastic reduction in the tree, shrub and nutritious grasslands vegetation, converting a drought-adapted mosaic environment into a fire-adapted seeder scrub, affecting the population of dependent fauna (Miller et al., 1999, 2005). In this scenario, some fire-sensitive plant species, as well as animals that depend on large extensions of infrequently burnt habitats were affected (Nix, 1982; Macphail, Jordon and Hill, 1993). On the other hand, some fire-adapted species extended their range at the expense of rainforest vegetation (Smith and Guyer, 1983). Intensive and prolonged use of fire-stick farming had an extensive effect on environments, resulting in the gradual and sustained transformation of Australian vegetation patterns from dry forests into savannahs and may be "*possibly the earliest demonstration of humans as an agent of environmental change*" (Bird, Hope and Taylor, 2004). Increased wildfires explain the palaeoenvironmental shift recorded in the Nullarbor region by which a floristically diverse plant community transformed into a fire-resistant chenopod shrub-steppe (Prideaux et al., 2007). Therefore, anthropogenic fires provoked important ecological disturbances (fire, habitat fragmentation or destruction, harassment…) that led to the final collapse of megafaunal populations, a process that has been called sitzkrieg -slow war of attrition- in opposition to the blitzkrieg overkill hypothesis (Mosimann and Martin, 1975; Diamond, 1989; Barsnosky et al., 2004). Despite all the above, recent studies contradict the traditional view that the arrival of modern humans to Australia, with its cultural practices of burning environments, was the trigger and direct cause of the collapse of populations of large mammals, as well as other species like birds and reptiles, of Australia (Sakaguchi et al., 2013; Westway, Olley and Grün, 2017).

Homo sapiens were not responsible for the collapse of large mammals

However, it has been demonstrated that no intensive firing of the Australian landscape existed before the Last Glacial Maximum (LGM) (Sakaguchi et al., 2013), which has been traditionally argued as the key mechanism in megafauna extinction (Miller et al., 1999; Johnson, 2005). Moreover, the Aboriginal firing of the landscape did not occur on any significant scale until the late Holocene (Blabk et al., 2008; Mooney et al., 2011). Thus, that two events -megafaunal extinction and human colonization of Sahul paleocontinent- occur at the same time does not necessarily imply that they are directly associated (Wroe and Field, 2001) since coincidence in time does not prove causality (Flannery, 1990). Moreover, it is not clear an overlap between both events existed, since the great majority of Pleistocene Australian sites are poorly dated and the understanding of faunal turnover during this time is almost non-existent (Field, Fillios and Wroe, 2008). Not only that, but also it remains to be elucidated whether the majority of the megafauna extinct taxa disappeared during late or middle Pleistocene, with major megafauna extinctions occurring around 130kya and further range contractions and extinctions throughout the last glacial cycle (Wroe and Field, 2006). Few localities have suggested a temporal coexistence of *Homo sapiens* and megafauna (Wroe and Field, 2006; Field et al., 2013). Recently, a study of *Zygomaturustrilobus*, the second-largest marsupial ever existed, from Willandra Lakes -a site continuously occupied by Aboriginal people from 50kya- coexisted between circa 15-20kya with *Homo sapiens* (depending on the exact moment we consider the beginning of the colonization of Australia took place) (Westaway et al., 2017). Thus, as the authors stated, *Zygomaturus* extinction did not occur until several thousand years of coexistence with modern humans (Westaway et al., 2017). In a recent exhaustive megadata analysis of 659 Australian megafauna fossil