Evidence of burning from bush fires in southern and east Africa and its relevance to hominin evolution

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Abstract

Early human fire use is of great scientific interest, but little comparative work has been undertaken across the ecological settings in which natural fire occurs, or on the taphonomy of fire and circumstances in which natural and humanly controlled fire could be confused. We present here results of experiments carried out with fire fronts from grass and bush land in South and East Africa. The work illustrates that in these circumstances hominins would have been able to walk with and exploit fires, emphasizing that there can be different levels of fire use. The results also indicate that traditional assumptions about the discrimination of these are not reliable. Grass fires pass through the landscape rapidly, in burns of less than 5 minutes duration, but areas of denser vegetation burn to much higher temperatures and for much longer. Trees are also caught in fires, and may burn back into their roots, baking sediments. Animal bones on the surface can also become burnt, so that presence of burnt bone has to be used with care as an indicator of human activity. Duration of burning, repeated nature of burning, and co-presence of features of human activity may give a better indication of human involvement.

Introduction

Studies of early fire have come to the fore in recent years, with important discoveries of new archaeological evidence at sites in Africa and other parts of the Old World, and new hypotheses about its evolutionary role (e.g. Berna et al. 2012; Wrangham 2009, 2017; Gowlett 2010, 2016; Parker et al. 2016) and significance in the biosphere (Archibald et al. 2012; Bond and Keeley 2005; Belcher et al. 2013; Bowman et al. 2011; Scott 2000, 2009, Roos et al. 2014; Scott et al. 2016). The subject of the human role remains controversial because evidence of most burning disappears very rapidly, and there are also possibilities of confusion of evidence of controlled fire and evidence of wild fire.

An understanding of early human fire use can be obtained from a number of sources, including physiological and genetic (evidence based on metabolism, digestion, or genetics is inevitably largely indirect), but the archaeological evidence has the potential to be the most direct, providing that there is an adequate framework for interpreting it (cf Sandgathe 2017).

Exploration of the issues of early fire use demands the availability of a set of 'actualistic' comparative material which remains largely lacking, despite important pioneering efforts (e.g. Bellomo 1993, 1994: the first fire ethology appears to be owed to Al-Jahiz: Stott 2012; Al-Jahiz 2003). The scope of such work needs to be expanded now, partly because of the great variety of ecological circumstances in which fire occurs, and partly because of poor understanding of when fire evidence is likely to be preserved or to decay. Here we present the results of observations and experiments concerned with African bush fires, which make available new information about burning temperatures and durations, and about effects on bone. We emphasize that this is a field study, not a laboratory study. Considerable efforts had to be made to control the fires, and to ensure that they ran across the target areas where measurement probes had been inserted.

Previous research

Evidence on patterns and consequences of burning have been presented a number of times (e.g; Alperson-Afil and Goren-Inbar 2010; Bliege Bird et al. 2012; Bond and Keeley 2005;

Davies et al. 2016; Griffin 2002; Perlès 1977; Scott 2000, 2009; Sergant et al. 2006; Vale 2002; see also Alperson-Afil 2017; Barkai et al. 2017; Dibble 2017; Henry 2017; Holdaway et al. 2017; White 2017). Bellomo's work (1993, 1994) remains one of the most general treatments of methodology, based on a number of experimental studies as well as literature, and aimed to give documentation to the main kinds of natural fire, as well as to the nature of hearths.

Bellomo's research was geared to discriminating human fire from natural fire. Like many authors, Bellomo was inclined to emphasise temperature as a discriminator. He also suggested that grass fires reached high temperatures only for a very short period (cf Clements 2010), and therefore do not create any considerable burning of materials. He set out criteria for recognising hearths. He believed that they could be discriminated from natural bole fires, regarding the latter as rare. In his experiments Bellomo found it difficult to generate tree stump fires, and he tended to minimise their role, even though they can occur at times even in rainforest environments (Tutin et al. 1996).

Some assumptions drawn from Bellomo's work are widespread, most especially that temperature is useful for discrimination of hearth fire and wild fire. The presence of burnt bone, although not much used by Bellomo, is frequently also taken as an indicator of human activity (e.g. Brain and Sillen 1988; Brain 2005; Bosinksi 2005): again further testing of the issues would be highly desirable, and this paper takes steps in that direction.

Pattern of experimental fire research

We report here on recent experiments and observations in South Africa and East Africa:

(1) Experiments in burning set up as part of landscape management at Florisbad Quaternary Research Station.
(2) The following of a bushfire and study of traces of previous bushfires at Soetdoring Nature Reserve near Florisbad
(3) The observation of very recent bushfires and charcoal burning at Kilombe farm in Kenya, together with the recording of temperature variations with depth in experimental campfires.

Figure 1 about here

In this work it was possible to compare some burning events as they happened, and the results of other fires which had occurred recently nearby. In this respect the pattern is similar to that in Robbins' classic study of the decay of Turkana huts, where he was able to compare some as they were abandoned with others which were in the process of collapse (Robbins 1973). Ideally one would follow a complete cycle of burning, decay of organic remains, and vegetation recovery, but this would involve great expense, and in any case some useful observations are the result of purely chance factors (e.g. encounter of a fire on a given day).

The research addressed three particular questions:

(1) To what extent do the temperatures observed in grassfires and brushfires match those commonly accepted in archaeological observations and interpretations?

(2) To what extent do tree fires occur, and to what extent are the traces left by these able to mimic hearths?

(3) To what extent do grassfires and bushfires affect surface bones?

The Fires - Outline

Most of our observations were made around Florisbad, about 40 km north of Bloemfontein in South Africa (fig. 1), where a reserve extends to the north of the museum (fig. 2). This research was stimulated by observation of an accidentally started bushfire close to the museum in 2008, and also by similar encounters with fires at Kilombe in Kenya, possibly inadvertently started by charcoal burners. The range burning at Florisbad, however, takes place as a means towards restoring native vegetation and improving grazing resources, rather than for the research. In total we were able to observe fire in grassland, in low scrub and in savanna (or riparian woodland) including groups of trees of up to ca. 5-8 metres height. We were able to determine effects on vegetation, and also on organic materials such as bone. In general, wind speeds were relatively low, of a few miles per hour.

In all cases fire fronts moved through relatively fast, with most immediate burning taking place within a space of a few minutes, and of less than 30 minutes even in the case of trees (figs 3-6 below). Temperatures, however, were exceedingly variable, according to type and density of burnt plant material, as demonstrated by measurements taken with thermocouples attached to long heat-resistant leads (see note for recording methods) (cf also Govender et al. 2006).

Fires at Florisbad Quaternary Research Centre and Museum

The Museum is set within a region of grassland and small karroid shrubs (sweet veld), with occasional trees, especially closer to water (see Janecke and du Preez 2005). Locally, an area of ca. 700 hectares had been farmed, historically, but has been museum land since 1980. Bush and scrub clearing by fire was organised in this area by the National Museum in 2012 and 2013. The aim of current conservation is to remedy the effects of over-grazing during past farm use, and to restore grassland veld vegetation which can support an antelope population. The land is situated at about 1250 metres, and descends gently to the north towards the Soutpan depression (Kuman et al. 1999; Scott and Brink 1992) (fig. 2).

Figure 2 about here

In the course of the systematic burns at Florisbad it was possible to measure burning temperatures near vegetation using thermocouples (see methods note). Additionally, we were able to place part-carcases of two antelope for study of burning efects, discussed below.

The burns took place over numbers of days in September 2012 and 2013, towards the end of winter, and before the onset of any rains. Around the world records show that many lightning-induced fires occur at the start of rains following a dry season (e.g. Gisbourne 1931; Johnson 1992): in all cases here the vegetation was in much the state of dryness which would come into contact with the first thunderstorms a few weeks later. Examples of the burning are described and explained below:

(1) Temperatures of burning in open grassland

Grass burns were conducted on a number of days when windspeeds were relatively low (burns were nto permitted when windspeeds were higher than about 16 kph). The grassland at Florisbad is made up by a variety of species similar to those at nearby Soetdoring (Janeke and du Preez 2005), sometimes occurring in dense stands, sometimes patchy. At Florisbad vegetation/grass height is generally 30-60 cm. The grasses were ignited easily, and burnt in moving fronts.

Figure 3 about here

Figure 3 illustrates measurements from two adjacent probes in open grassland. In one of these temperature rapidly rose from ambient to more than 500° C, but in two minutes it had fallen back sharply towards ambient (i.e. 20-30° C). The other probe records a lower peak (possibly because the highest temperature endured for just a few seconds), but temperature of >200 ° C was recorded for four minutes.

Two measurements made on *Themeda triandra*, red grass, the following day in similar conditions, indicate a similar picture with peak temperature reached and falling right back within 3 minutes (fig. 4; see also S fig. 1).

Fig 4 about here

(2) Temperatures of burning: small shrubs and grasses

This example from the same suite of fires demonstrates temperatures and speed of burning in grassland in relation to a small shrub (GPS Point 358: 28 45.159S/26 05.974; 17/09/2012): small karroid shrubs occur patchily in the area (Janecke and du Preez 2005), and may significantly affect intensity of burning. Four thermocouples were set, at a height of 60 cm on a bush, of 10 cm, of 25 cm on adjacent small stump, and at height of 5 cm in grassy brush. At 9.45 am ambient temperatures on these were 18-24 ° C. Fire was set locally at 10.03 am. As the front hit the area around 10.05 am, temperatures rose to 151, 240, 40 and 183 ° C respectively. All temperatures then sharply declined, except that the grass brush temperature rose briefly to 500 ° C. By 10.30 am temperatures had fallen to 43, 39, 27 and 25 ° C s – closing towards the original ambient temperatures. A piece of cattle dung 2 m from the bush was recorded burning at 605 ° C at 10.16 am, and at 1045 ° C at 10.37 am. Figure 5 illustrates temperatures in a further similar case of bush and grass burning.

Fig. 5 about here

Another case illustrates the way in which the initial rapid burn can lead to continued burning and higher temperatures in localised areas of denser vegetation (fig. 6). One probe was attached to a small prickly bush, another to densely matted grass. The bush burnt fiercely and rapidly, without very high temperature, but temperatures of the burning grass rose to towards 600 °C, and were maintained at greater than 200° C for around 15 minutes. Most interesting, adjacent dung was ignited, but it did not burn rapidly: rather the temperature was rising towards 500 °C as the others declined, and it had the effect of prolonging local burning to at least 30 minutes. In this case the longer burning may reflect input of oily material from the bush, coupled with the dense matting of the grass. Figures 4 and 5 also show a slight bounce-back of temperature, possibly because woody material took longer to ignite and burn than the grasses.

Fig. 6 about here

The principal finding is that although most grass fires had a predictably rapid burning plume structure, time duration and temperature profile (cf Clements 2010), in practice wide ranges of temperature variation were observed. Grassfires were of the order of 300 °C, but the plume spike rose to ca 700 °C as gases ignited (cf Clements 2010). The temperature and duration of burning were notably raised when the fire caught hold of shrubs.

Fires at Soetdoring Nature Reserve.

Soetdoering lies about 5 km south of Florisbad. Observations from three bushfires at Soetdoring provided further evidence about burning of vegetation, especially trees, and also of bone. The game reserve flanks a reservoir extending behind the Krugersdrift dam on the Modder River, and lies 40 km north of Bloemfontein, and about 5 km from the Florisbad museum site. The landscape is to the eye a mosaic of grassland and savannah, and in botanic terms it is part of the Grassland Biome of the sweet veld, and similarly regarded as a mosaic dominated either by grasses or by dwarf karroid shrubs (such as *Chrysocoma ciliata*, *Pentzia incana*, *Pentzia globosa* and *Rosenia humilis*) (Janecke and du Preez 2005). Larger trees are found towards the river, including especially sweet thorn (soetdoring), a species of *Acacia*.

We were able to observe and investigate evidence from three bushfires:

1. a fire in progress on Sunday 23 September 2012
2. a fire of July/August 2012, about six weeks old at the time of observation.
3. a fire of Monday 10 September 2012 observed at the end of the burn and through the following week

The approximate extents of the burns are shown in Figure 7. The cause of ignition of Fire 3 was reported to be a barbecue fire. Fires 1 and 2 may also have been caused by human activities, such as the dropping of a cigarette. We discuss the fires out of chronological order so as to follow a train of argument.

Figure 7 about here

Fire 1 – Bush Fire followed in action

This fire was observed by chance at the Reserve on Sunday 23 September 2012. It was immediately visible from about 2 km as it began to consume trees (fig.S2). The cause of ignition is not known, but there did not appear to be any visitors in the area of the park. We were able to follow the fire for more than 500 m, up to the point where it came up to a creek, which it eventually passed around.

It was striking that the fire very rapidly consumed trees (fig. S3), moving rapidly and loudly, but also that the burning was selective, with adjacent trees and even grass patches often unaffected. We were able to observe the way in which trunks burnt through at the height of 1-1.5 metres, and in which the upper parts of trees were often entirely consumed so that nothing remained except fine ash within a few minutes.

In general, the fire burnt out by the water's edge, but in places it consumed reed beds, with dramatic flaming and smoke. We were not able to use temperature probes, but inferred that that there was a great range of burning temperatures even very locally.

Fire 2 – trees and associated debris left by fire

This fire, the earliest of the three, was not observed by us: it must have been similar in character to Fire 3, but perhaps hotter judging by the damage, and more extensive (fig. 7). An area was recorded about 700 m south of the believed fire source at (28 49.693 S 26

03.088 E). Here the fire had passed through a group of trees forming a sparse copse around 25 metres across, and two areas of 15 x 9 metres were plotted (fig. S3).

The burning illustrated several features characteristic of the area. The trees had burned to a varied degree. One stump indicated a cut by flames at about 1.5 metres (fig. S4). At least two or three trees had been consumed entirely, with only fine ash trails preserving the pattern of the fallen trunks and branches

In several instances the trees had burnt right back into their roots, creating fire-baked zones up to two metres across (figs S5,S6). These are of particular interest in the sense that they could possibly mimic hearths, and create clasts of baked clay possibly similar to those found at Chesowanja (Gowlett et al. 1981). We excavated a section across one of these combustion zones, and found that the baked zone extended to ca. 20 cm depth (fig. S6), almost certainly indicating high temperature maintained for considerable time (we discuss hearth temperatures further below in relation to experiments at Kilombe). In general, from inspection of quite a number of such burnt out stumps, we observe that they shouldcould be distinguishable from hearths becauseif they preserve the shape of spreading descending roots (a criterion also noted by Bellomo 1993). Even where there is a wide open depression, the roots can be observed at the margins, sometimes with charred wood preserved (Note that Melson and Potts (2002) described other ways in which natural baking of sediments can occur in East African environments).

Last, there were scattered bones on the surface by the trees, of a duiker-sized bovid. The scapula and humerus were quite heavily burned, suggesting that the brush had burned quite intensely around them.

Fire 3 – bushfire and effects on animal carcases

This fire, close to the main entrance of Soetdoring Park, we were able to observe while some areas were still smouldering. It gave the best opportunities to study effects on the bones of carcases. These were of animals that had died and decayed down to their skeletons before the fire, perhaps by a year or more. In each case these had been lying in grass, and there is no doubt from the taphonomic indications discussed below that the animals had already been dead for at least several months and their soft parts were fully decomposed at the time that the fire passed.

a. bones of medium-size bovid (Hartebeest: Alcelaphus buselaphus).

The skeleton was essentially complete, with the bones scattered across an axis of about 4 metres, and bone positions partly representing past anatomical connexions. Bones were variably burnt, with the skull and horn cores having suffered particularly, perhaps because they stood a few centimetres higher above the surface than the other bones. The skull is most burnt (fig. S7) and separated into two pieces. Nasal passages were the focus of burning (the main part of the cranium had been lying on its base, with the frontal uppermost). In contrast, the hemi-mandibles were scarcely burnt except for the tip of the condyles on both sides. The scapulae had lain flat on the ground: one was charred brown on the dorsal surface, the other just on the dorsal spine. Both sides of the pelvis are quite strongly charred, especially around the pubic area, but also around the margins of the ilia (fig. S8).

On the limb bones there was very little sign of burning except light charring around the distal right humerus, probably after the epiphysis had detached (the equivalent ephiphysis was in position on the other side, with no obvious burning). The ribs showed little sign of burning, except at vertebral ends, where there was some charring.

Charring of the vertebrae is very variable, prominent in some pieces, absent in others, but the place of burning varies between equivalent vertebrae. Dorsal spines were most commonly charred.

b. Jackal (Canis mesomelas)

The jackal had apparently become ensnared at the foot of an old wire fence, probably no more than few months previously, as some of its pelt remained as a mass. Its skeleton is virtually complete; again its bones were variably burnt. Some show little or no trace of burning, but others including the flat plates of vertebral spines, are considerably charred:

Skull/mandible: slight charring around nasal aperture
Cervical vertebrae: charring of spines, above or below; one more than the others
Thoracic vertebrae: heaviest burning on the spines. 6 badly charred versus 5 scarcely charred/
Lumbar vertebrae: minor burning to spines.
Pelvis: some charring to margin of ilium on one side.
Ribs: about half of them charred at one end, usually proximal end

Upper and lower limbs: very little visible damage, with just slight charring to ridge of one scapula. Foot bones, metapodials still articulated, uncharred.

c. Small antelope

The small duiker was about 70 % complete: one forelimb had vanished, two feet were missing, as also most of the thoracic vertebrae. The ribs were fragmented. Fire damage was follows:

- Skull – light charring of edges of nasal cavity
- Mandibles: light charring of tip of one condyle
- Cervical vertebrae: darkening, tip of one spine
- Thoracic vertebrae: 1 complete, lightly browned
- Lumbar vertebrae: 5 articulating: plain charring of dorsal spines, very light charring of lateral spine tips.
- Forelimb: taphonomic damage to plate of scapula: charring of the chewed edge, and on ridge. None to cup.
- Humerus: distal end missing, light chewing; sharp bone edge considerably charred
- Radio-ulna: proximal end considerably charred; radius fragmented, charred on one edge
- Pelvis: ilia had separated, light chewing of tips and edges; light charring of pubic area. Light charring to parts of both femurs (also taphonomic damage from chewing) and one tibia, and one calcaeum. No obvious burning damage to the foot parts preserved.

Experimental burning of antelope carcases at Florisbad

We set out to determine whether fresh antelope carcases would become burnt in a comparable way, in terms of visible damage to bones, and whether presence of meat would affect the burning. To this end two culled carcasses, a black wildebeest and a blesbok, were acquired from the Caledon Nature Reserve (a reserve managed by the Free State Provincial Government):

Black wildebeest:

- This was a young adult black wildebeest male, with the third molar erupted, but not yet in wear. The carcass was complete, but skinned and with the intestines removed.
- At Florisbad we defleshed the carcass, except for the right front limb, which was detached and kept separately.

Blesbok:

- This was an adult blesbok female with a broken left metacarpal that was incompletely healed. (The break must have occurred a few seasons ago, since there was much additional bone growth around the break, which forms in an attempt to stabilise the bone. From the pelvis it is clear that she had had several calves).
- The carcass was received intact, with skin still on, but with the intestines removed.
- The carcass was kept as it was.

We wanted to see the effect of the grass (veld) fire on 1) defleshed bone (the carcass of the black wildebeest without the right front limb), 2) bone with flesh on, but without skin (the right front limb of the black wildebeest), and 3) bone with flesh and skin on (the carcass of the blesbok). Therefore, we put out the defleshed black wildebeest carcass, the right front limb with flesh still on and the blesbok caracass with flesh and skin on. These parts were left in the path of the fire so that the fire could run over them, as if in a natural fire.

Temperature probes were attached to the limbs of the blesbok and to the wildebeest limb. In an effort to maximise burning, the specimens were set beside a fairly large bush (otherwise the situation was as in the other grass fires described). Figure 8 shows the resultant temperature profile and burning duration.

The two curves suggest that the temperature for one thermocouple was maximised by being in the plume of burning, the other minimised perhaps by being on the top of the carcase and not exposed to direct flame. They do however have similar profiles, showing the usual rapid heating with the fire front, following by a cooling off through about 10-15 minutes.

Figure 8 about here.

When inspected, the blesbok skeleton, which had meat and skin attached, showed very few signs of burning. These were confined largely to lower parts of limbs. The left scapula spine was darkened; the lower part of the left front limb was darkened (distal shaft of metacarpal) or became white or grey and brittle (phalanges). Tibia and metatarsal of the left hind limb also became white and brittle. The right front limb of the black wildebeest, with its flesh but no skin, showed only a slight darkening to the proximal lateral part of the radius-ulna. In summary, we found that in the passing fire the meat attached to the blesbok and to the right limb of the wildebeest did not heat sufficiently to cook substantially, and that it served to protect the bones.

The rest of the skeleton of the wildebeest, which was defleshed and placed in a separate firepath, could have been more directly exposed to burning due to the defleshing, but in fact, there were very few signs of burning other than slight darkening here and there. The blades of the ilia were slightly darkened and brittle; as with the blesbok, the tibiae were affected, with the left in particular being brittle and crumbly.

Experimental campfires at Kilombe, Kenya

Experimental fires were carried out by S.H. on clay rich substrates in the area of the archaeological site of Kilombe, Kenya (Gowlett et al. 2015) and their aim was to provide a further check on the common statement that campfires burn in the range 300-800 ^{o} C (e.g. Bellomo 1993, 1994 as previously cited; also Gowlett et al. 1981). On the first day, the ground was prepared by removing the first 5 cm of soil and then marking out an area of 150 cm by 150 cm. K-type thermocouples were used in order to take temperature readings at regular intervals of 15 mins during burning over a period of 1 hour 30 mins. This procedure was repeated for a further campfire on the second day. The thermocouples (T) were arranged in two rows, one in the centre of the fire and the second on the peripheral of the fire and at different depths of 1-2cm (T2), 3-4 cm (T3) and 6-7 cm (T4). A further thermocouple was used to record the temperature of the actual flames during burning (T1), i.e. it was lodged above the fire. The fuel used was local wood, chiefly *Acacia*.

The highest temperatures were recorded by thermocouple T1 and T2 which were recording the temperatures of the actual flames, and at 1-2cm depth respectively. Maximum values for T1 varied between 480 to 620 ^{o} C and T2 varied between 380 and 402 ^{o} C. Temperatures recorded at depth were much lower and did not exceed maximum temperatures of 248 ^{o} C at 3-4 cm (thermocouple T3) and 150 ^{o} C at 6-7 cm (thermocouple T4). Thermocouples T5-T7 placed at the periphery of the campfire did not record temperatures above 58 ^{o} C. Temperatures were similar for the second 90 minute fire the following day.

These temperatures clearly occupy a similar range to those of the passing grassfires. The suggestions that temperatures of hearths/campfires can range from 300-800^{o} C is likely to be accurate in relation to the flames but not necessarily in terms of the firing temperature of the underlying soils/sediments – a point which may have implications for the use of temperature measurements to identify human activity in the archaeological record. Much lower temperatures than are generally attributed to human campfires were recorded during the experimental campfires at Kilombe, specifically at depths of 3-4 cm, although at a depth of 1-2cm temperatures just over 400 ^{o} C were recorded. This may in part be due to the relatively short burning times of the particular experiments. (The fire fronts described above also often passed without consuming much of the lowest level of grass and dry plant debris suggesting that there would be little if any effect on the underlying sediments). In other camp fires we have seen considerable baking of sediments, which did not occur here, suggesting that longer duration experiments and also variations in fire size are needed for establishing a range of comparisons. There is an issue of preservation as complete deposits rarely survive on early hominin sites, so that traces of a temperature gradient could easily be lost. The figures suggest again that temperature on its own is not a reliable indicator for discriminating between human-controlled and natural fire, but also emphasize that various factors influence the degree of baking of sediments.

Discussion

The fire experiments detailed here bring together a number of points which may sometimes be common knowledge in forest fire studies (e.g. papers in Scott et al. 2016), but which have not been established or applied in strict archaeological terms. We have concentrated here on documentation of the visible taphonomy of fire remains, rather than on behavioural interpretations. The experiments were often carried out as ancillary activities to range management or other research, and clearly mark only a beginning to work of this kind. They were carried out in the open veld, in the context of fire hazards, and considerable efforts had to be made to ensure that the fires passed over the target thermocouples, and to keep the fires within control. Our efforts therefore concentrated on establishing temperatures and rates of burning. As we took the opportunities presented by chance factors, such as the ongoing accidental fires at Soetdoring, we were not always able to have prior choice of the experimental materials. We do not know exactly how long bone distributions had lain on the surface, or how much the collagen in the bones had decayed. With temperatures and durations of burning established, however, such factors can be much more easily studied in experimental situations which do not involve bushfires, but which rather make use of smaller fixed experimental fires, or even ovens. Similar observations can be made about the burning of sediments. We believe that most campfires, like those at Kilombe, do not generate a great deal of heat below, and do not bake sediments to any depth. The passing bushfires also often have little effect on the lowest vegetation and plant roots. On the other hand, tree burns generate great heat, and can bake sediments through 20 cm or more. Continuing controlled work on the burning of sediments is clearly valuable for establishing a broader picture (Aldeias et al. 2017).

At the level of animal behaviour, it is plain that for all its great importance fire does not create resources, rather it converts or attracts resources. The fires studied in South Africa were set in a low resource area, and although there were signs of effects on rare invertebrates, birds and small animals such as tortoises, all of which would be of interest to hunter-gatherers, these were very infrequent in these particular landscapes. In another environment, hominins might find that the density of resources would give far higher incentives for fire-following.. As far back as the ninth century AD Al-Jahiz commented on the large numbers of animal species attracted to a fire (Stott 2012). In the fires observed by us the combination of relatively low vegetation fuel load and low wind speeds allowed safe transit for humans around the fire areas, as has also been observed for chimps in west African savanna (Pruetz 2017; Pruetz and LaDuke 2010), but the greater intensity of the burn at Soetdoring on 23 September dramatically highlighted the power of fire, and particularly its ability to destroy trees very rapidly.

Stumpfires are of particular interest here as they were generated with difficulty in Bellomo's (1993, 1994) work and feature little in his scheme, but could potentially lead to creation of hearth-like features. It is therefore useful that we observed evidence of stump fires numerous times in the Soetdoring fires. In the African savannas many trees are fire resistant, and we have rarely observed evidence of stump fires such as presented here, although evidence of tree stump fires has been observed at Chesowanja in Kenya, where a wooded area was destroyed in the 1930s (Clark and Harris 1985), and charred stumps were still visible in recent years.

We observed baked clay evidence, similar to that observed in the Soetdoring fires, in Kenya when a bushfire took place in January 2011, progressing from NE to SW across large parts of Kilombe farm. Our group narrowly missed observing the fire, but was able to search its consequential evidence some months later in July 2011. One burnt stump recorded by us at Kilombe appears (from oral evidence and inspection) to have been a dead tree with its core already rotted away. Sometimes these are found at the heart of a termite mound which has built up around the tree, and in that case baked clay would also be produced in a burn. Most of the trees burnt at Soetdoring, however, were certainly alive.

At Soetdoring there was a common scenario of a fire plume from grass and shrub fire which as it passed would attack the tree boles at a height of around 1.5 metres. They would then burn through at this point, with the upper part dropping on its base (figs S3, S4); both parts would then continue to burn, the stump downwards into its roots, and the upper part outwards towards its extremities, which sometimes remained unburnt. The obvious archaeological relevance is that such fires burn hot, certainly up to 800 degrees – the full range of hearth fires - and that they can also create baked areas.

Although this evidence seems a cautionary tale – that natural tree fires may cause hearth-sized baked features - it is encouraging that they also corroborated an observation of Bellomo (1993) that the shape of the tree root features is distinctive and could be distinguishable from a hearth. As indicated in figures S5 and S6 the spreading roots directed the shape of the combustion feature produced.

At Soetdoring one of us (AC) located one such tree burn shortly after the fire. Ash filled the hollow in the baked clay. Not only did it have a temperature of around 400 degrees C, this was maintained for several days afterwards. It suggests the possibility that in the early days of interactions with fire hominins could easily have been drawn to any feature which naturally retained a high temperature for a long period.

The studies which we report can be related to early human behaviour, and the likelihood of its preservation in a number of ways. Chance factors ought to be emphasised both in the primary creation of a record, and its later preservation. It seems likely that in most circumstances the great majority of hearths will be eroded away through a period of time, generally perhaps the century following use. Most environments are erosional: even in a depositional environment out-movements of material may balance in-movement of sediment. It is worth restating a point made by Richard Preece that most European open sites with hearths are preserved through coincidence with tufaceous deposits (cf Preece et al. 2006, 2007); most others are preserved through rapid deposition of silts as at Pincevent (Julien 2003), or loess, as on the Russian plains (Klein 1973; Holliday et al. 2007). In Africa, there is a similar rarity of open air hearths, even in relatively recent periods where human use of fire is well accepted (Florisbad is another example coinciding with tufa: Kuman et al. 1999; Henderson 2001). Animals bones, too, have a relatively short survival time on the surface, in Africa ~20 years (see Gifford 1980). It is questionable then whether any of the sites studied in our experiments would have passed into a long term record. Studies such as those of Davies et al. (2016) and Holdaway et al. (2017) can cast further light on the probabilities through modelling and large scale field survey of hearth distributions, which is difficult or impossible for earlier periods.

Conclusions

The field experiments around Florisbad and at Kilombe emphasise a number of points, on a landscape scale, and in relation to detailed archaeological evidence. A first point is the great visibility of bushfires, and that they can often be followed on the ground with reasonable safety. They attract attention, and can signify the possibility that food resources will be available.

Next, temperature is in no sense a reliable discriminator between grass fires and humanly-managed fires. Both clearly range through 200-800^{o} C on a regular basis.

Baked clay is created by stump fires, by falling burning trunks, and by human activities. The natural instances as observed by us result from intense combustion of tree wood. These instances should have the character – for instance in magnetic studies – of a single high temperature peak followed by very gradual cooling. Any trace of repeated episodes of heating would be a very strong indicator of human activity. The stump fires also have a different physical conformation from hearth ‘bowls’.

Bone lying on the surface during a wild fire can clearly become charred, even in rapidly passing grass fires. Paradoxically, meaty bones appear far less likely to become charred. The co-incidence of charring and butchery marks on bone, as at Swartkrans (Brain and Sillen 1988, Brain 2005, Pickering 2012), appears to argue far more strongly for human fire use than does charring of bone alone. Again, points made about repeatedness of human fire use in one locality are relevant (Alperson-Afil and Goren-Inbar 2010; Gowlett 2010): repeated fires may well be necessary for bones with combined evidence of charring and butchery to result in any number.

In these experimental fires animal dung turned out to be one of the most important factors in the prolongation of burning. It can frequently be seen smouldering after a fire front has passed, and it does not seem speculative to suggest that hominins would have been aware of this. The gathering and carrying of burning dung could have been one of the first steps for hominins becoming engaged with fire use. It is worth restating another point, that natural fire is rarely a good chef. On numbers of occasions, here and elsewhere, we have noted that a fire passes too fast to complete cooking, or conversely, it may burn eggs completely. There would be a strong incentive for hominins following fires to intervene, even to a minor degree, to improve the quality of cooking – either by putting food resources back into the fire, or pulling them out. The signs of continued burning behind the fire front, in dung, and stumps, might be a strong pull to humans to engage in that kind of activity.

If foraging is the most natural route into fire using, as might be suggested by the large numbers of bird and animal fire followers (Berthold et al. 2001; Gowlett 2010), it would require for hominins a very detailed knowledge of potential resources and the way in which these could be managed - the beginnings of ‘fire farming’, which can be seen as a somewhat different problem from the origins of hearth fire which are the focus of many studies.

Methods Note

Temperatures were measured with the use of long thermocouples. The tip lengths of ca. 100 cm were heat resistant up to 1100 degrees Celsius. The remaining lengths of ca. 12 metres could withstand 300 degrees and were therefore buried at a shallow depth. Data were logged on a standard temperature recorder from a fire lane, either at intervals, or continuously recorded with the aid of a video camera.

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Figures

1 Map of Africa showing fire sites mentioned in the text.

2 The museum reserve area at Florisbad. The grassland extends from the museum at the southern end to the edge of the Soutpan pan at the north (Satellite imagery courtesy of Google Earth).

3 Temperature measurements of two fire fronts in grassland (veld) at Florisbad.

4 Temperature measurements of two fire fronts in *Themeda triandra* (red grass) stands).

5 Temperature measurements on small bush and grasses at Florisbad.

6 Temperature measurements on prickly bush, dense matted grass and dung. The dung would have ignited shortly after the fire front passed, but a thermocouple was inserted only when the dung was noted smoking as the other fires subsided.

7 Soetdoring Nature Reserve: approximate outlines of the fires in 2012 (Base map courtesy of Google Earth). The fires were all in wooded grassland along the south bank of the Modder river.

8 Temperature measurements of Wildebeest and Blesbok limb bones in grass and bush fire at Florisbad.

Supplement Figures

S1 Fire front in grassland, Florisbad (19 September 2012).

S2 Bush fire of 23 September 2012 at Soetdoring: first observation from a distance of ca 2 km shortly after the fire started.

S3 Soetdoring: Plots of two zones within a copse destroyed during the July 2012 fire. Bones (bottom right) of a small antelope were severely charred. The finds of burnt out stumps, ash distribution and bones in this area illustrate the way in which natural burnt features can occur on a similar scale to those in a human settlement.

S4 A tree stump cut by flames at height of ca. 1.5 metres (see also Fig. 10 top left).

S5 Example of a tree burnt right back into the roots (see also Fig. 10 top right).

S6 A baked zone excavated. From the burnt out stump (centre) only charcoal survives, but a charred radiating root is preserved (right).

S7 Charred cranium of hartebeest (Soetdoring): the scattered bones of the skeleton were passed over by the fire of 10 September 2012.

S8 Pelvic region of the hartebeest, showing differential burning, especially around the pubic region and the ilia (scale bar 20 cm).

Figs 1-4 stay same
Fig 5 becomes Fig S1
Figs 6-8 become Figs 5-7
Fig 9-15 become Figs S2-S8
Fig 16 becomes Fig 8

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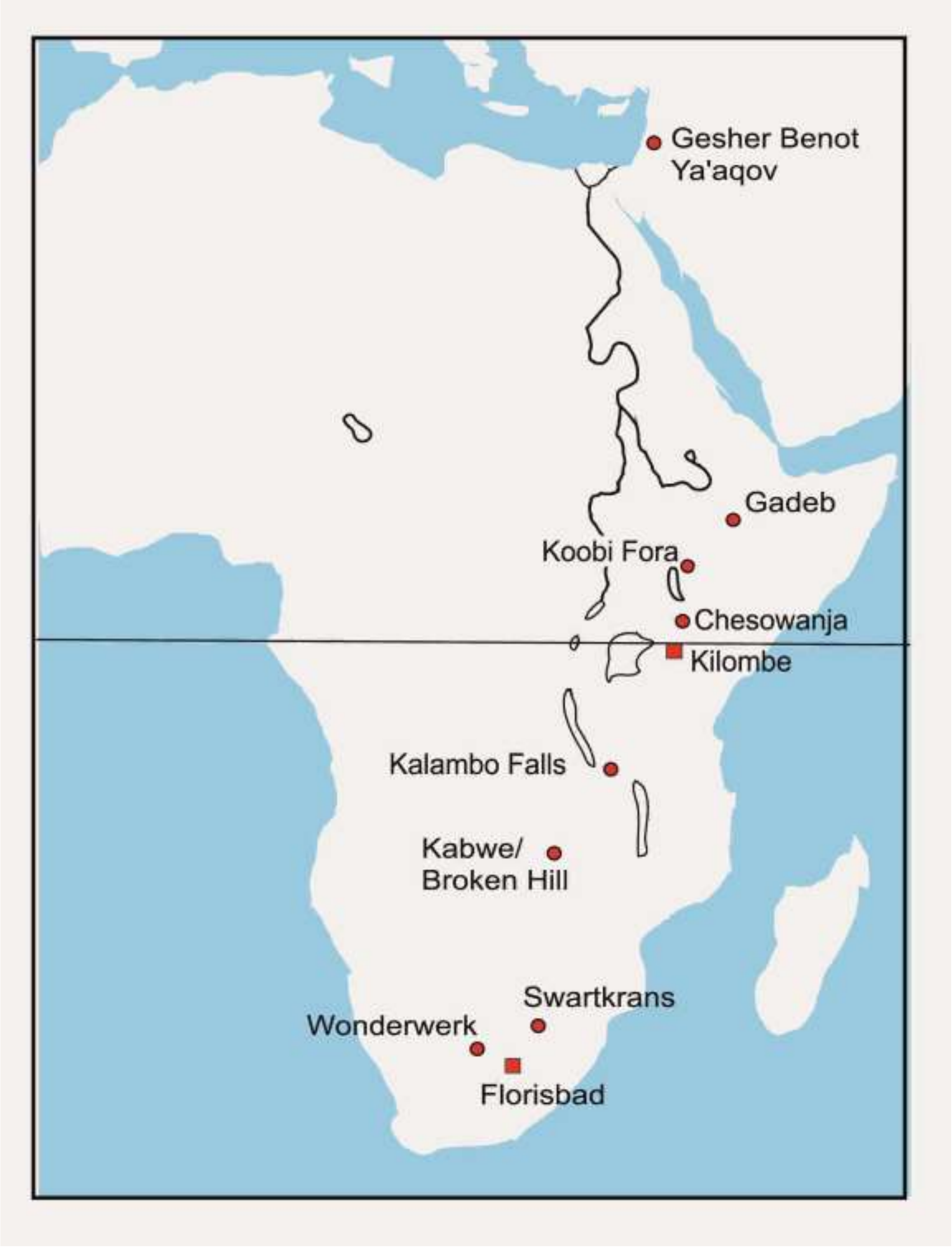
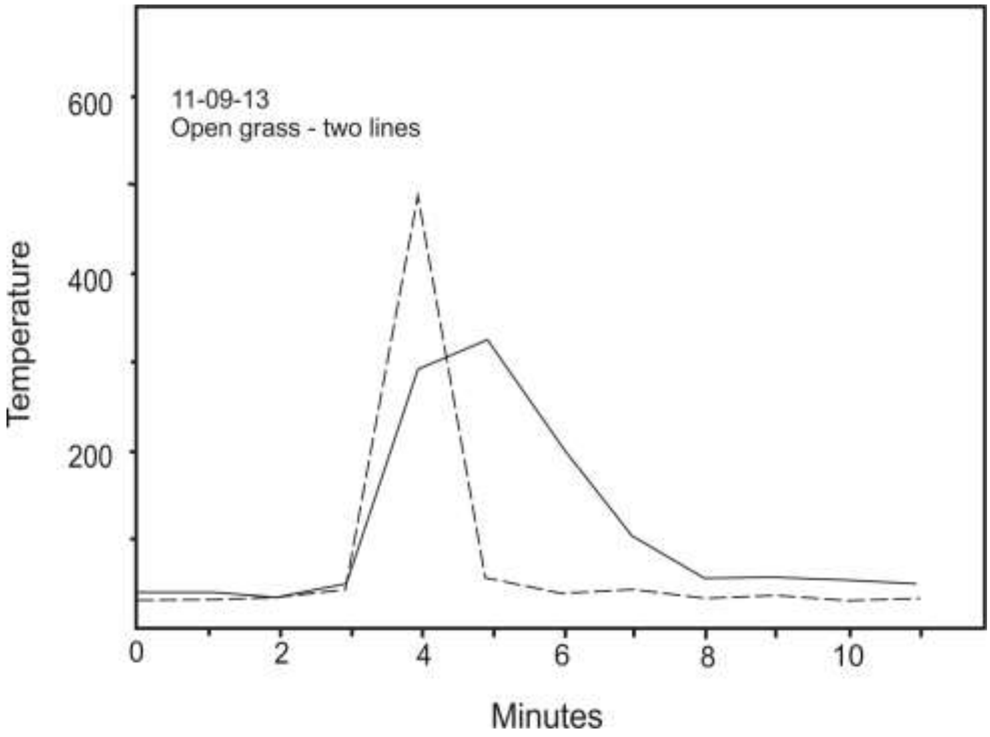
1 Map of Africa showing fire sites mentioned in the text.



2 The museum reserve area at Florisbad. The grassland extends from the museum at the southern end to the edge of the Soutpan pan at the north.

Temperature measurements of two fire fronts in grassland (veld) at Florisbad.



4 Temperature measurements of two fire fronts in *Themeda triandra* (red grass) stands

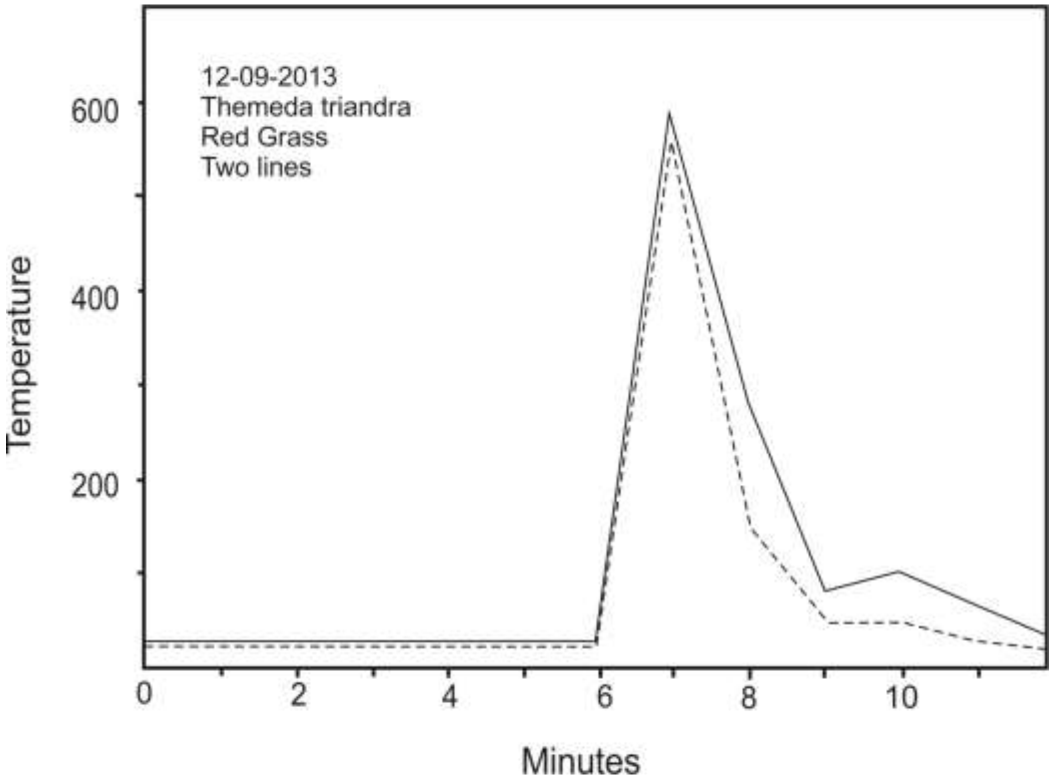
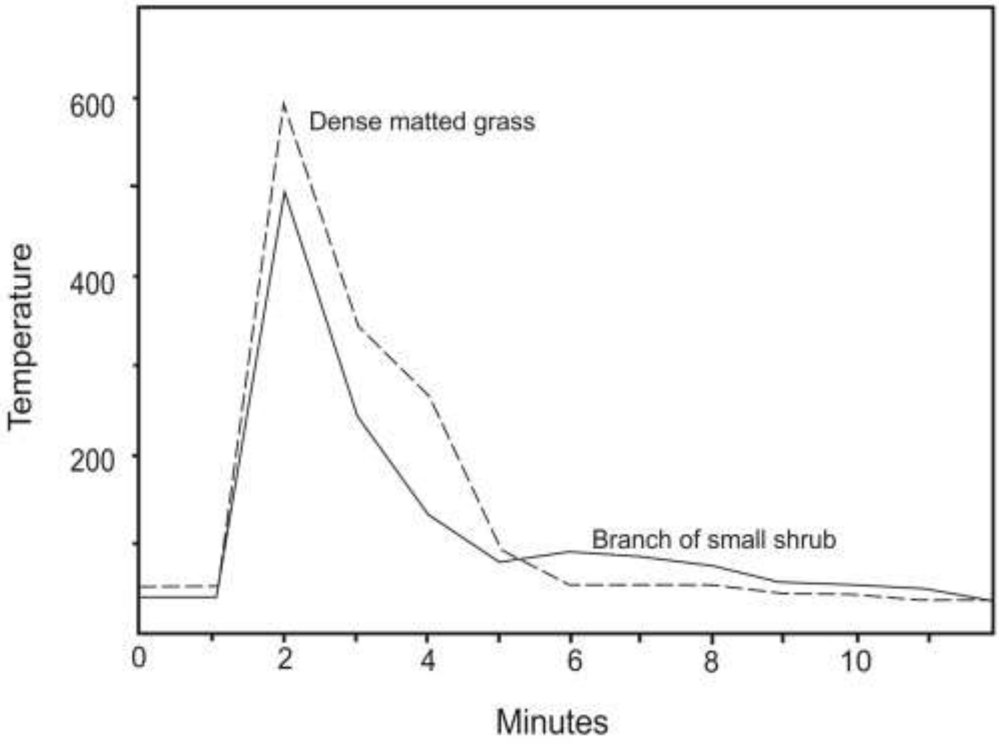
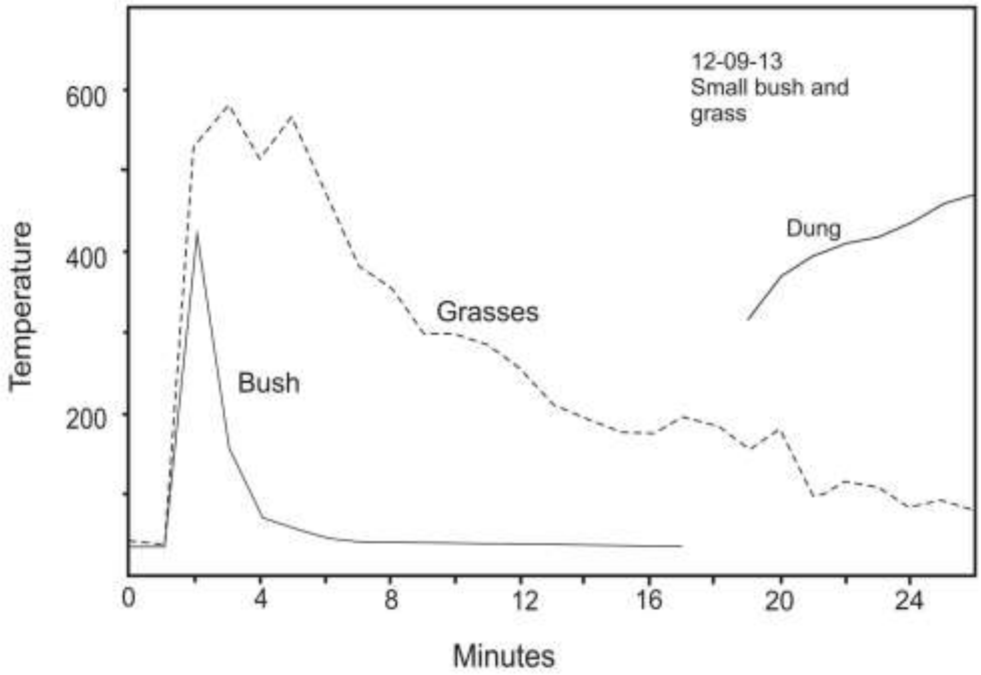


Fig S1 Fire front in grassland, Florisbad (19 September 2012).

5 Temperature measurements on small bush and grasses at Florisbad.



6 Temperature measurements on prickly bush, dense matted grass and dung.



7 Soetdoring Nature Reserve: approximate outlines of the fires in 2012.

Fig. S2 Bush fire of 23 September 2012 at Soetdoring: first observation from a distance of ca 2 km

Fig. S3 Soetdoring: Plot of a copse destroyed during the July 2012 fire. Bones (bottom right) of a small antelope were severely charred.

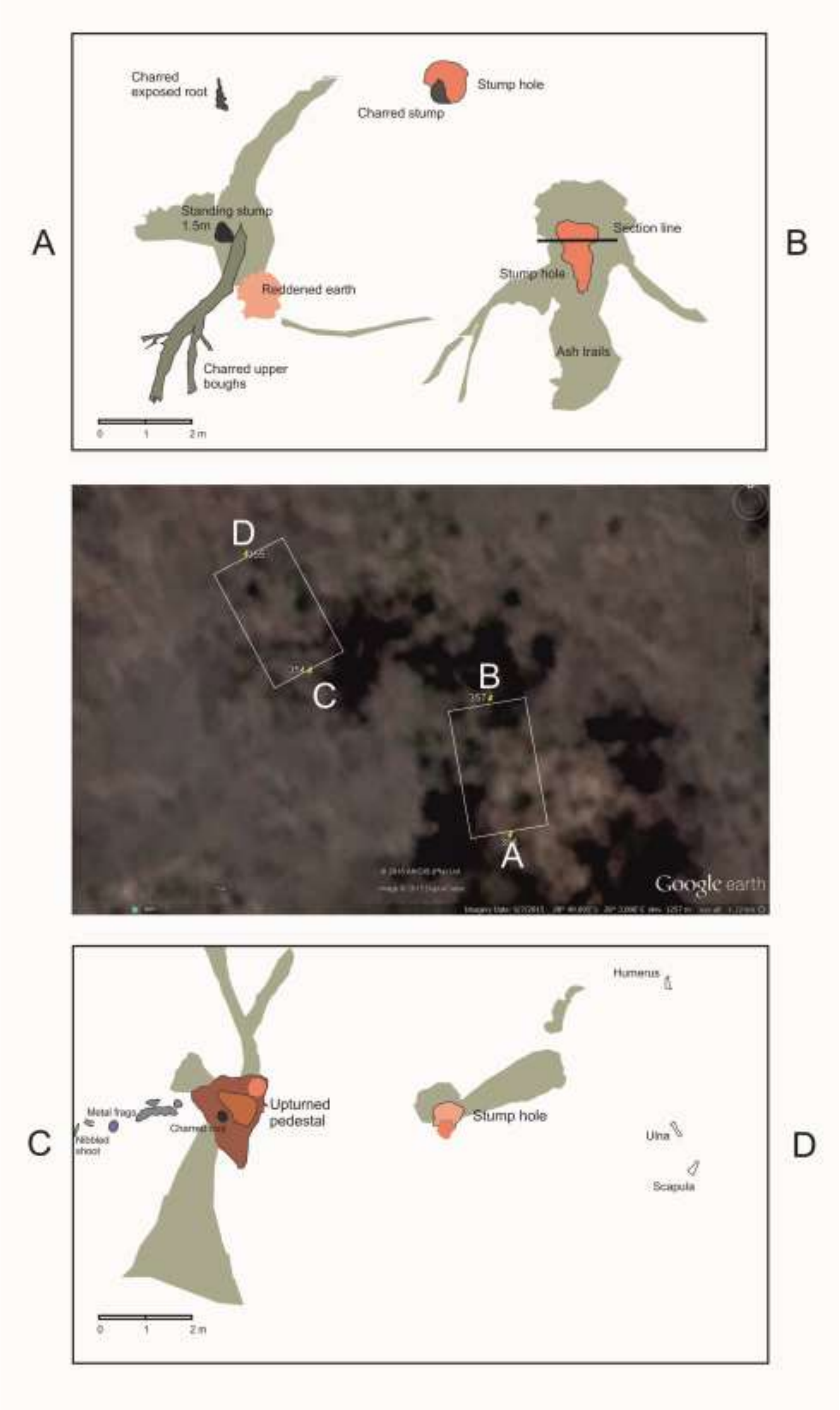


Fig. S4 A stump cut by flames at height of ca. 1.5 metres (see also Fig. 10 top left).

Fig. S5 Example of a tree burnt right back into the roots (see also Fig. 10 top right).

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8 Temperature measurements of Wildebeest and Blesbok limb bones in grass and bush fire.