Exploring the relationship between Aboriginal population indices and fire in Australia over the last 20,000 years

Alan N. Williams^{*1}, Scott Mooney², Scott A. Sisson³, Jennifer Marlon⁴

1. ^{*}Fenner School of Environment and Society, The Australian National University, Canberra ACT 0200, Australia. T: +61(0)408 203 180; E: alan.williams@anu.edu.au

2. School of Biological, Earth & Environmental Sciences, UNSW Australia, NSW 2052, Australia.

3. School of Mathematics and Statistics, UNSW Australia, NSW 2052, Australia.

4. Yale University, School of Forestry & Environmental Studies, New Haven, CT, USA

Abstract

The extent of prehistoric human impact on the environment is a contentious topic in various palaeo-environmental sciences. The long history of humans in Australia and its extensive fire-prone biota makes this continent a key research area for better characterization of prehistoric human-fire interactions. Here we use statistically robust cross-correlation of archaeological radiocarbon data (n=4,102 ages from 1,616 sites) and a new synthesis of charcoal records (n=155 sites) to test for any relationship between people and fire over the last 20,000 years at continental and regional (25-45°S) scales. We find that the statistical correlation between the two datasets is weak at both spatial scales, with short-lived synchronous responses only in the terminal Pleistocene-Holocene transition, at the onset of the mid-Holocene climatic optimum (~10-7ka) and during significant transitions of El Niño Southern Oscillation (~5-4ka and 1.2-0.8ka). One interpretation of this is that Aboriginal populations were implementing ‘fire-stick farming’ only intermittently during periods of societal stress resulting from climatic variability. However, the synchronicity of the correlations with climate changes, along with

the low populations through much of this time, suggests both datasets were independently responding to external climatic forcing. Under either scenario, a lack of significant change in the charcoal record implies that there were no long-lasting impacts to the environmental biota, and macro-scale palaeoenvironmental records prior to European colonisation largely reflect responses to non-human influences. While we do not discount the possibility of systematic or deliberate manipulation of fire regimes at local spatial scales, we conclude that human control of fire by prehistoric people in Australia is not evident at broad landscape levels. This conclusion contradicts persistent suggestions of Australian-wide land management and the pervasiveness of the impacts of ‘fire-stick farming’.

Keywords: Fire-stick farming, Aboriginal demography, charcoal, radiocarbon data.

Introduction

The systematic modification of the landscape by Aboriginal people using fire was first proposed as a concept in the 19th Century (Curr, 1886), but it was not until Tindale (1959), and especially Jones (1969) who coined the term ‘fire-stick farming’, that it became a focus for archaeological and Quaternary palaeoenvironmental research. Jones (1969) suggested that fire was an integral part of the Australian prehistoric economy and this led to the widespread modification of biota. His hypothesis led to considerable debate, and there is still little agreement on the extent to which Aboriginal people were land managers (e.g. Hallam, 1975; Bliege-Bird et al., 2008, 2013), or how much observed ecological changes over the last 50,000 years should be attributed to them (e.g. Horton, 1982; Kershaw, 1986; Benson & Redpath, 1997; Bowman, 1998; Miller et al. 2005; Mooney et al. 2011; Notaro et al., 2011; Bird et al., 2013; Sakaguchi et al., 2013). These issues have extended into political and conservation management literature, and similarly remain contentious (e.g. Bowman, 1998).

Despite the debate, significant relevant advances have been made in the last decade, with analysis of contemporary Aboriginal community practices and satellite imagery of post-contact landscapes providing clear evidence of anthropogenic burning (e.g. Burrows et al. 2006; Bliege-Bird et al., 2008, 2013; Bowman et al., 2008; Bird et al., 2009; Smith, 2013). These human behavioral and ecological studies show that fire was used for a range of activities, including for hunting, 'cleaning up country', protection of religious sites and stands of fire-sensitive trees, and asserting ownership of land (Smith, 2013). An incidental consequence of these practices was an enhancement of short-term productivity, increasing patch diversity, reduction in the risk of wildfires through more regular and frequent small-scale burning, and an increased mosaic of small patches of vegetation at different successional stages across the landscape (e.g. Bliege-Bird et al. 2013).

Bliege-Bird et al. (2008) hypothesized that these behaviors become increasingly important only in the mid-late Holocene as larger, more closer settled, populations inhibited mobility, and forced a broadening of diet to include lower calorific resources (see also Burrows et al. 2006; Bird et al. 2009; Williams et al., submitted); they further suggested that populations would not have been sedentary or dense enough to have developed this practice in the late Pleistocene - a finding more recently re-iterated by Williams (2013).

However, these studies are all primarily based on human behavior and landscapes observed over the last 50 years, and any extrapolation further back in time is conjectural. Spatially, these observations are also constrained to the arid parts of Australia, and their applicability elsewhere has yet to be established. Further, this ethnographic work suggests that anthropogenic burning was extremely localised and with only transient biotic impacts (e.g. Bowman et al., 2008; Burrows et al., 2010), and therefore may not be easily discernable in palaeoenvironmental (e.g. palynological or charcoal) records. Few attempts have been made to directly correlate archaeological and palaeoenvironmental records, and for the most part any relationship remains equivocal (e.g. ; Head, 1989; Black et al., 2006; Mooney et al.,

2007, 2011; Bird et al., 2013). Mooney et al. (2011) standardised and compiled charcoal records from 223 sites across Australasia producing a record of biomass burning for the last 70ka. The lack of significant change in fire at about the accepted time of the human colonization of Australia (~50ka), as well as the lack of congruence between a subset of the archaeological data used in this paper and the fire record led Mooney et al. (2011) to conclude that fire activity in Australia was unlikely to reflect human activity.

We explore the potential relationship between people and fire in Australia over 20,000 years with the most comprehensive continent-wide archaeological and charcoal datasets currently available. We analyze these proxies with statistically robust techniques that have not previously been applied to comparable palaeoenvironmental or archaeological data. Our primary aim was to test if anthropogenic burning could be discerned, and if so when it was initiated. We first test these concepts at a continental scale and then repeat this analysis on the southern portion of the continent, which is arguably more climatically homogenous, where prehistoric populations have been described as larger and more sedentary (Williams, 2013; Williams et al., submitted), and where our datasets are strongest.

The Proxies and their Interpretation

Charcoal

The abundance of charcoal in sediments is widely used as an indicator of past fire activity (e.g. Patterson *et al* 1987; MacDonald *et al* 1991) and has been used to reconstruct fire histories at more than 700 sites across the globe (Daniau et al., 2012). The use of charcoal as a proxy of fire dates to Iversen (1941), and primarily relies on the optical identification and quantification of charcoal in sediments. Significant advances in charcoal methods have placed the discipline on a quantitative footing, exploiting the accumulation (*aka* influx) of charcoal (either no./cm²/yr or mm²/cm²/yr) in sediments; the statistical analysis of these data allowing the derivation of fire frequency through time (Whitlock and Millspaugh 1996, Long *et al*

1998); and most recently methods allowing the synthesis of multiple charcoal records across a variety of spatial scales (e.g. Power et al. 2010; Marlon et al. 2013).

While widespread, the interpretation of charcoal data can be complex (e.g. Conedera et al. 2009). As a proxy of past fire events, it is confounded by several inter-connected issues: the taphonomy of charcoal (including the transport, delivery and preservation) is not consistent and can be dependent on the nature of the fire, post-fire events, spatial relationships involving fire-to-catchment size ratios, and proximity of the fire to the site of deposition. The inter-connected components of a fire regime can also influence charcoal accumulation and hence confuse the interpretation of any record. In Australia, the prehistoric fire regime is often characterised as consisting of regular, small fires, for example in a complex mosaic of burnt and unburnt vegetation. This might mean that fire is ubiquitous but not necessarily ‘visible’ in a charcoal record, unlike human use of fire in the post-European landscape, which shows up clearly in Australian paleofire data (Marlon et al. 2013). Frequent fire may also influence vegetation (e.g. fuel loads and type) and perhaps lead to less intense fires, or more grass and hence lower charcoal production. This ambiguity is starkly evident in Singh et al.’s (1981) landmark chapter in *Fire and the Australian Biota*, which is the first publication to discuss charcoal records across multiple sites in Australia. In this work the complex interplay between charcoal, fire frequency and fuel loads meant that an increase in charcoal was interpreted as an increase in fire activity at one site (Lake George) and less fire at another (Lashmar’s Lagoon). To overcome this, here we consider *any* change in charcoal (not just an increase or decrease) in the statistical examination of the relationship between fire and people.

Archaeological Radiocarbon Data

As a proxy for Aboriginal demography, we use radiocarbon data from archaeological sites across Australia. This ‘dates as data’ approach is becoming increasingly commonplace in the archaeological literature, and recent work has continued to improve its reliability (e.g. Smith et al. 2008; Williams et al. 2008, 2010; Collard et al., 2010; Peros et al. 2010; Buchanan et al.,

2011; Williams, 2012, 2013, Shennan et al. 2013). Nonetheless, analysis and interpretation is complex and has several limitations. In Australia, the two main criticisms of the technique include: 1) how detrital charcoal in archaeological sites (i.e. samples not recovered from features directly attributable to humans such as hearths, burials, etc) relates to the archaeological record; and 2) whether the radiocarbon data reflects demographic change, or changing behaviour in hunter-gatherer societies (i.e. more dates equals greater mobility, rather than more people). Recent work by Williams (2012, 2013) has addressed these issues and demonstrated that detrital charcoal data correlates well with other radiocarbon data directly attributable to human activity within archaeological sites and can be reliably used; and that the radiocarbon data correlates well with other archaeological indices (such as artefact discard rates), and provides greater certainty that the data reflects demographic change. Here, we similarly assume the data can be broadly attributed to demographic change and our confidence is bolstered by trends in the Australian data that seemingly closely reflect potential forcing factors (e.g. independent palaeoclimatic information).

Materials and Methods

Charcoal

We use a new compilation of charcoal data representing sites within Australia (n=155) (Figure 1); these are a subset of Mooney et al.'s (2011) Australasian data, supplemented with 6 new sites (see Supplementary Data). In some cases (10 sites, detailed in the Supplementary Data), the data have been slightly revised (for example resulting from improved chronological control) compared to that used in Mooney et al. (2011). We also developed a regional subset of these records (n=125) located south of 25° (that is covering southern Australia, bound by the latitudes of 25 - 45° S and 110 - 155°E). The data consist of charcoal influx data from a wide variety of lakes and lagoons situated across the continent, although with a bias towards the eastern Australian coast (Figure 1). As described in the Supplementary Data, approximately 25% of the sites have a medium-to-high resolution (>15 samples/ka) and 42 of the sites (~27%) extend beyond 14ka.

These data were combined using z-score techniques developed in Power et al. (2010). The technique standardizes the individual charcoal records and synthesizes them into one curve representing biomass burning over the last 20ka (see Supplementary Data).

Archaeological Radiocarbon Data

We use the most comprehensive archaeological radiocarbon dataset for the Australian continent assembled to date (Williams et al., 2014). This consists of 5,044 radiocarbon ages from 1,748 sites across Australia (of which 4,102 from 1,616 sites were usable in the analysis); and 2,625 dates from 972 sites between 25-45°S (Figure 1). The data are distributed across the continent, but also have an east coast bias, in part reflecting the better resources for hunter-gatherers in this region in the past, but also the focus of archaeological research historically (see Williams et al., 2014 for a critique of the dataset). Temporally, the data covers the entire 20,000 year period being investigated, although Holocene ages do dominate the dataset (n=3,729).

These data were converted into time-series curves using techniques outlined in Williams (2013). The techniques included the calibration and binning of the data to produce the basic time-series; the taphonomic correction of open site data using an exponential decay type function, to subdue over-represented Holocene data, and increase more sparse Pleistocene ages; and conversion of the data into an annual change, considered to reflect growth rates (GR_{Ann}), and allowing the development of quantitative populations estimates. All of these techniques and methods are outlined in detail in the Supplementary Data.

Figure 1. Map of the 1,748 sites containing archaeological radiocarbon data and the location of the 155 charcoal records.

Statistical Correlations

We computed the statistical correlations between the charcoal and archaeological datasets in overlapping time-periods of 2000-year intervals width ($n=100$ observations per interval), from 0.06 – 20ka.

In order to better test for any statistical correlations between the charcoal and archaeological datasets, we first performed pre-whitening of the series within each time interval in order to avoid spurious correlations. This is a well-known phenomenon for strongly auto-correlated datasets (e.g. Brockwell and Davis, 1991). Pre-whitening involves first fitting an ARIMA (autoregressive integrated moving average) model to the archaeological dataset, which is expected to lead the palaeo-fire record. Then the residual series of both charcoal and archaeological datasets under this fitted model were extracted. Cross correlations with both positive and negative time lags (between -320 and +320 years) between the two residual

series can then be safely calculated. Here, significant correlation at positive lags means that the archaeological data is correlated with biomass burning in the future, whereas significant negative time lag suggests that biomass burning is leading the population proxy. Symmetry in the significant correlation over positive and negative lags indicates that the series are in phase with each other, and suggests that both series are influenced by a common driver.

Results

The continental archaeological data is presented in Figure 2. Both average annual population growth rates (Figure 2:A) and the archaeological data (Figure 2:B) show significant change over the last 20ka, with initially very low populations through the Terminal Pleistocene (18 - 12ka), steadily increasing from 11ka to their highest levels in the last 2,000 years. Notable declines in the data are evident at 18ka, 14 - 12ka, 5ka and 3ka; with peaks occurring at 20ka (primarily stemming from focused archaeological investigation in the Willandra Lakes system), 16ka, 11ka, 8ka, 4.5ka and 1ka. An extensive, and stable, period of growth appears to occur between 11 - 6ka. Demographic change appears to be driven by populations in the southeast of Australia, and constraining the data to 25 - 45°S (Figure 3) has little effect on these overall trends.

The continent-wide compilation of charcoal data (Figure 2:C) reveals an upward trend in the early part of the record (~19.5 - 15.7ka), which continues at a slower incline between 14 - 8ka. The data are relatively stable through the Holocene, but arguably shows a slight downward trend from 8 - 3ka, after which this trend reverses, becoming a very clear increase during the last 1.4ka. Superimposed on these trends are some variations including decreases centred on 14.1ka and 11.5ka, and a peak at 12.6ka. When considering only data from 25 - 45°S (Figure 3:B), these trends remain broadly the same, although several peaks and troughs intensify. This is most evident through increasing variability in the record during the mid-Holocene, and through troughs at 14.1ka, 11.5ka and the enhanced peak at 12.6ka. The Holocene trend in the southern compilation becomes clearer, with an upward trend in the

early Holocene, peaking at 6ka - some 2,000 years later than the peak in the Australia-wide compilation. The mid-to-late Holocene downward trend (6 - 3ka) is also evident in the southern compilation, as is the sharp late Holocene increase, beginning at 1.2ka and notably steeper in the last 500 years.

Comparison of the archaeological and charcoal data reveals few correlations (Figures 2 and 3). Visually, there is weak positive correlation immediately after the LGM (18-14ka) and through the mid-Holocene climatic optimum (8-6ka); and inverse correlation (increasing population/decreasing fire) between ~14-8ka, and 3-0ka. Statistical analysis does not support these observations however (Figure 4). Intermittent positive cross correlation is evident between the continent-wide uncorrected radiocarbon data and the charcoal compilation between 15-10ka and 5-2.5ka, with the strongest relationship evident in the late Pleistocene-Holocene transition (Figure 4A). When considering the southern latitudes, positive cross correlation between the uncorrected radiocarbon and the charcoal compilations is evident throughout the late Pleistocene, but is notable at the onset of the mid Holocene Climatic Optimum (MHCO) (~10-7ka) and the apparent intensification of ENSO (~5-3ka) (Figure 4B). However, the symmetrical nature of these cross correlations suggest that both indices are responding to external forcing, rather than one leading the other. This is made all the more likely by the cross correlations often being constrained within well-known climatic events such as the Antarctic Cold Reversal (ACR), the late Pleistocene-Holocene transition or when ENSO seemingly gains in intensity after ~5ka.

The corrected radiocarbon data also show little cross correlation with the charcoal record (Figures 4C and 4D). There are a few brief intermittent positive correlations (the archaeological 'explanatory variable' leading the 'dependent' palaeo-fire record), but these are likely to be random noise which would be expected if there was no relationship. (With an alpha level of 0.05, 5% of all correlations might be "significant" just by chance, even when there is no relationship.) In these diagrams there is a notable absence of negative correlations,

not even the expected random noise as seen in the positive correlations. This indicates that there is no evidence of the archaeological proxies leading the biomass burning proxy and evidence against leading in the other direction.

Discussion and Conclusions

Using new standardization and regionalization methods, we explore the relationship between archaeological and charcoal records in Australia, as proxies for human demography and fire, over the last 20,000 years. While acknowledging the limitations of the approach, we find little correlation between Aboriginal population and fire activity in Australia at either a continental or regional scale.

When exploring the statistical results, some of the strongest positive correlation between the uncorrected archaeological and charcoal data occurred in the terminal Pleistocene (~18-10ka), with both records low through the LGM, gradually increasing into the early Holocene, and with a slight decrease through the ACR. It is unlikely, however, that such a small population through this period (<50,000 or ~1/250km²) (population estimates are based on Williams, 2013 and discussed further in Supplementary Data) would have had the ability or requirement to undertake widespread landscape-scale burning. Applying an ideal free distribution model, such low numbers of people would more likely have moved into more productive patches to sustain their needs, rather than expend energy to broaden their diet via large-scale landscape modification (Bird & O'Connell, 2006; Kennett et al., 2006) - a process that may have admittedly resulted in some burning for ease of mobility across the landscape.

Figure 2. The continental records of birth rates, archaeological data, and palaeo-fire from 20-0ka. A) A record of GR_{ANN} , effectively birth rates, developed for Australia by Williams (2013), with increasing (decreasing) values indicative of growing (falling) populations. B) human activity as derived by radiocarbon data ($n=4,576$); uncorrected data is presented as a stacked bar chart with white bars = rockshelters and black bars = open sites; taphonomically corrected data after Williams (2012) are presented as grey bars with a 600-year moving average trendline. C) z-score reconstruction of biomass burning from 155 charcoal records after Mooney et al. (2011) (curves have been smoothed using a window of 400 years (red) and a window of 100 years (bold black) to emphasize the centennial-scale variability; bootstrapped confidence intervals are based on a 400-year smoothing of the curves (grey). Key climatic events are also shown: Last Glacial Maximum (LGM), Antarctic Climate Reversal (ACR), mid Holocene climatic optimum (MHCO), the onset of modern El Niño-Southern Oscillation variability (ENSO), and increasing La Niña (LN) conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Figure 3. The southern latitude (25-45°S) records of birth rates, archaeological data, and palaeo-fire from 20-0ka. A) A record of GR_{ANN} , effectively birth rates, developed for Australia by Williams (2013), with increasing (decreasing) values indicative of growing (falling) populations. B) human activity as derived by radiocarbon data ($n=2,625$) (uncorrected data is presented as a stacked bar chart with white bars = rockshelters and black bars = open sites; taphonomically corrected data are presented as grey bars with a 600-year moving average trendline). C) z-score reconstruction of biomass burning from 125 palaeo-fire records after Mooney et al. (2011) (curves have been smoothed using a window of 400 years (red) and a window of 100 years (bold black) to emphasize the centennial-scale variability; bootstrapped confidence intervals are based on a 400year smoothing of the curves (grey). Key climatic events are also shown: Last Glacial Maximum (LGM), Antarctic Climate Reversal (ACR), mid Holocene climatic optimum (MHCO), the onset of modern El Niño-Southern Oscillation variability (ENSO), and increasing La Niña (LN) conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Figure 4. Statistical autoregressive integrated moving-average (ARIMA) correlations of the continental uncorrected (A) and corrected (C) archaeological radiocarbon data and the palaeofire record ($n=155$); and of the southern latitudes ($25-45^{\circ}\text{S}$) uncorrected (B) and corrected (D) archaeological radiocarbon data and the palaeo-fire record ($n=125$). All datasets were pre-whitened before correlations were computed. Correlation is presented in colours with white and yellow indicating strong and moderate positive correlation, respectively; and maroon and red indicating strong and moderate negative correlation, respectively. Orange indicates no significant correlation. Key climatic events are also shown: Last Glacial Maximum (LGM), Antarctic Climate Reversal (ACR), mid Holocene climatic optimum (MHCO), the onset of modern El Niño-Southern Oscillation variability (ENSO), and increasing La Niña (LN) conditions. Figures E-H are scatterplots showing the same data used in the ARIMA model of A-D, specifically depicting the relationship between the archaeological radiocarbon data and the palaeofire record: for the continental (E) and southern latitudes ($25-45^{\circ}\text{S}$) (F) uncorrected radiocarbon data; and the continental (G) and southern latitudes ($25-45^{\circ}\text{S}$) (H) corrected radiocarbon data. The shading provides an indication of time, with darker colours indicative of more recent periods. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

The co-temporal trends between the two indices can more readily be explained by the re-establishment of interglacial conditions, including the northerly summer monsoon and mid-latitude westerlies (Griffiths et al., 2009; Johnson et al., 1999; Magee et al., 2004; Wyrwoll & Miller, 2001), and associated sources of moisture. This return to positive moisture balances across a wider geographical area of Australia/Sahul allowed populations to grow and expand out of *refugia* (Williams et al. 2013) (and thereby increasing the data) and simultaneously, increased primary biomass productivity (*a priori* fuel load). Such conditions may have also resulted in greater thunderstorm activity, leading to significantly more natural fires via cloud-to-ground lightning strikes than previously. The modern distribution of lightning strikes (e.g. WWLLN, 2014) is related to humidity and hence shows a tropical bias: this might explain the relatively stronger late Pleistocene increase in fire in the Australian-wide compilation compared to that of the southern latitudes (compare Figure 4:A with 4:B). The onset of the post-glacial monsoon at ~13ka (Johnson et al., 1999; Wyrwoll & Miller, 2001; Magee et al., 2004) probably experienced more lightning and natural fire within the monsoon belt. If we consider increasing archaeological data to reflect mobility, rather than population, this interpretation similarly cannot explain the apparent bias in the tropical region with most data occurring in the southeast. It is, however, acknowledged that biota may have been constrained within the same *refugia* as humans during the glacial, and as such anthropogenic fire may have had a far greater influence than at other times in the past.

In the southern latitudes (and to a lesser extent the entire continent), strong correlation between the indices occurred at the onset of the MHCO (10-7ka) (Reeves et al., 2013). This is a period of population growth (Figures 4A and 4B) and widespread expansion or re-expansion into previously uninhabited areas (Smith, 2013; Williams, 2013; Williams et al. submitted). The spread and regional establishment across the interior coincides with the spread of *Pama-Nyungan* language and the distribution of Panaramitee rock art style, and indicates the beginnings of a more socially connected people with some level of corporate identity (McConvell, 1996; Smith et al., 2009; Smith, 2013). In combination with

increasingly complex food procurement strategies (such as fish traps, eel traps and swamp management (McNiven et al., 2012; Ulm 2013)), these behaviors are suggestive of a more sedentary population making some attempt at low-level food production (Smith, 2001), especially in the temperate regions; and this may have resulted in the use of fire as a tool in these activities (patch productivity, encouraging game, etc).

Increasing biomass productivity resulting from enhanced moisture during this time (e.g. peak water depth in western Victoria at ~7.2ka (Wilkins et al. 2013)) may also have led to anthropogenic burning to aid in movement across a more densely vegetated landscape. It is therefore quite believable that this human-fire correlation reflects the initiation of anthropogenic burning. However, given the technologies and behaviours initiated in the MHCO continued up to European Contact, any correlation should have been continuous throughout the last 5-7,000 years, but this does not prove to be the case. Rather, any relationship between people and fire are short-lived and occur only at the onset of significant climatic transitions, including the El Niño Southern Oscillation (ENSO) intensification (~4.5-2ka) (Moy et al., 2002; Rein et al. 2005), and strong La Niña (LN) conditions at 1.2-0.8ka (Goodwin et al., 2014). We therefore suggest that they are more likely to reflect periods when strong external forcing brings people and fire into synchronicity; their short-lived nature representing societal reorganization under, and in tandem with, new environmental conditions. Haberle and Ledru (2001) and Haberle et al. (2001) also found increased synchronicity across widely located tropical sites between synthesised charcoal records and regional climate proxies during times of climatic instability, suggesting that climatic inconstancy and fire are broadly associated (see also Daniau et al. 2010; Marlon et al. 2008).

We see similar strong synchronous responses at the onset of, and during ENSO, most notably in the southern latitudes. The onset of ENSO was characterized by generally drier (Reeves et al., 2013), more variable conditions, impacting biomass (*a priori* fuel loads) and resulting in a number of hunter-gatherer responses, specifically: a decline in populations (although they

remained significantly higher than in the past likely inhibiting mobility), a broadening of diet, and increasing investment in procurement and handling techniques in productive habitats, with abandonment of more marginal areas (Ugan et al., 2003; Bird & O'Connell, 2006; Ulm, 2011; Veth et al., 2011; Asmussen et al., 2012; Smith, 2013; Williams, 2013; Williams et al., submitted; *cf.* Hiscock 1994; Attenbrow et al., 2009). It is at this time during the mid-late Holocene, when increasing technological investment was occurring that strategic and/or social use of fire would most likely have been implemented (Bliege-Bird et al., 2008). However, if evident at a continental or regional scale, anthropogenic burning should be observable as a significant increase in charcoal, reflecting greater numbers of fires lit, or alternatively a sharp decline as more regular mosaic burning reduced the magnitude and size of fires - neither is evident based on our results.

The last 2,000 years saw improving climatic conditions and continuing population growth, most likely through the technological innovations and strategies developed in the MHCO, and further refined during ENSO (Smith & Ross, 2008; Williams et al., submitted). Williams (2013) suggest populations were in the order of 1 million ($<1/10\text{km}^2$), resulting in demographic packing and strong territorial boundaries (Lourandos, 1997; David, 2002; Bird & O'Connell, 2006; Ross, 2013; Smith, 2013). Such behavior would have significantly reduced the availability of unoccupied patches, and the ability to move across the landscape for resources (Bird & O'Connell, 2006). Greater investment in food procurement strategies, in combination with diet broadening was almost certainly the result (Ugan et al., 2003; Bird & O'Connell, 2006); and again a probable time for patchwork burning to be implemented. However, again the data shows no evidence of humans influencing the fire record.

Based on the data and discussion above, we believe that there remain only two plausible scenarios. (1) Aboriginal people only adopted the use of fire during periods of significant climatic variability, when perhaps established food procurement strategies failed and short term productivity increase was required. Patchwork burning was a short-lived behaviour until

equilibrium was reached and then put aside for alternate strategies. If this proves correct, then observations of the ethnographic fire regime, rather than representing a well-established behaviour, may simply be reflecting a short-lived response to the impact and disruption to Aboriginal societies by European colonization.

Alternatively (2), the archaeological and charcoal data are responding to external climatic forcing, and have no relationship to each other at a regional or continental scale. This is most evident between 13 - 8ka when archaeological data are clearly increasing, but charcoal data shows no sustained trend. If the onset of an ethnographic fire regime is to be believed, and considered to extend into at least the late Holocene, there appears no significant change in the charcoal record, which remains relatively constant throughout the last 10,000 years. This strongly suggests that the influence of Aboriginal populations on the environment and biota was minor or at least spatially constrained (Mooney et al. 2011; Sakaguchi et al., 2013; *cf.* Gammage, 2011), and left no long term or lasting changes. While our data does not extend back to the continent's initial human colonization, these results for the last 20,000 years - when Aboriginal populations were greatest and most likely to influence fire regimes on a large-scale - suggest it is unlikely that anthropogenic burning by small hunter-gatherer groups would have been able to significantly alter environments and biota enough to have played a role in megafauna extinctions earlier in the Pleistocene (Bird et al. 2013; Sakaguchi et al., 2013; Wroe et al. 2013). We do, however, acknowledge that our analysis does not extend prior to the LGM, and so we have not tested this hypothesis. Further, if this does prove the case, it means that macro-scale palaeoenvironmental records may be able to largely discount prehistoric anthropogenic influence as one possible interpretation. This is in stark contrast to the sharp upward trajectory in our charcoal data at 0.2ka when European colonization had a clear and widespread impact.

We cannot provide any definitive conclusion as to whether (1) or (2) is correct, although we believe a strong argument has been made for (2). Regardless, both are testable: fine-resolution

spatially-explicit studies in locations with documented ethnographic fire regimes should further clarify the potential impact of the anthropogenic use of fire. In Australia, at least, we also require further empirical research to explore the relationship between known fire events of different scales and intensity and the contemporary charcoal record. Future research needs to explore the complexity and interpretations of both proxies, preferably in tandem, rather than in isolation – a finding similarly made by Bowman (1998) and Bird et al. (2013).

Acknowledgements

SM acknowledges funding support of DP120104322 (Baker & Mooney: Has C20th fire changed?) and the Temperate Highland Peat Swamps on Sandstone Research Program Joint Venture. JRM was supported by NSF Grant #BCS-1437074. We would like to thank everyone who contributed Australian charcoal data to the Global Palaeofire Working Group and also thank Anne-Laure Daniau (CNRS, France), Patrick Bartlein (U.Oregon, Eugene OR) and Mike Smith (Australian National Museum, Canberra ACT) for advice and comments on this work. We'd like to acknowledge Sandy Harrison's work towards expanding the Global Charcoal Database and the IGBP Fast-Track and Cross-Project Initiative on Fire and the PAGES Integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS) program and the Land Use and Cover Working Group. We thank two anonymous reviewers for formal review.

References

Asmussen, B. & McInnes, P. (2012) Assessing the impact of mid-to-late Holocene ENSO-driven climate change on toxic *Macrozamia* seed use: A 5000 year record from eastern Australia. *Journal of Archaeological Science*, **40**, 471-480.

Attenbrow, V., Robertson, G. & Hiscock, P. (2009) The changing abundance of backed artefacts in south-eastern Australia: a response to Holocene climate change? *Journal of Archaeological Science*, **36**, 2765-2770.

- Bamforth, D.B. & Grund, B. (2012) Radiocarbon calibration curves, summed probability distributions, and early Paleoindian population trends in North America. *Journal of Archaeological Science*, **39**, 1768-1774.
- Beaton J.M. (1983) Does intensification account for changes in the Australian Holocene archaeological record. *Archaeology in Oceania*, **18**, 94 –97.
- Benson J. & Redpath P. (1997) The nature of pre-European native vegetation in south-eastern Australia: a critique of Ryan, D.G., Ryan, J.R. & Starr, B.J. (1995). *Australian Landscape – observations of explorers and early settlers. Cunninghamia*, **5**, 285–328.
- Bird, D.W. & O’Connell, J.F. (2006) Behavioral ecology and archaeology. *Journal of Archaeological Research*, **14**(2), 143-188.
- Bird D.W., Bliege Bird R. & Codding B.F. (2009) In pursuit of mobile prey: Martu hunting strategies and archaeofaunal interpretation. *American Antiquity*, **74**, 3–29.
- Bird, M.I., Hutley, L.B., Lawes, M.J., Lloyd, J., Luly, J.G., Ridd, P.V., Roberts, R.G., Ulm, S. & Wurster, C.M. (2013) Humans, megafauna and environmental change in tropical Australia. *Journal of Quaternary Science*, **28**, 439-452.
- Black, M. & Mooney, S.D. (2006) Holocene fire history from the greater blue mountains world heritage area, New South Wales, Australia: the climate, humans and fire nexus. *Regional Environmental Change*, **6**, 41-51.
- Bliege-Bird, R., Bird, D.W., Codding, B.F., Parker, C.H. & Jones, J.H. (2008) The ‘fire-stick farming’ hypothesis: Australian Aboriginal foraging strategies, biodiversity and

anthropogenic fire mosaics. *Proceedings of the National Academy of Sciences*, **105**(39),
14796-14801.

Bliege-Bird, R., Taylor, N., Coddington, B.F. & Bird, D.W. (2013) Niche construction and
Dreaming logic: Aboriginal patch mosaic burning and varanid lizards (*Varanus gouldii*)
in Australia. *Proceedings of the Royal Society B*, **280**, 20132297.

Bowman, D. (1998) Tansley Review No. 101 – the impact of Aboriginal landscape
burning on the Australian biota. *New Phytologist*, **140**, 385-410.

Bowman, D.M.J.S., Boggs, G.S. & Prior, L.D. (2008) Fire maintains an *Acacia aneura*
shrubland – *Triodia* grassland mosaic in central Australia. *Journal of Arid Environments*,
72, 34-47.

Brockwell P. J. & Davis, R. A. (1991) *Time Series: Theory and Methods*, 2nd edn.
Springer-Verlag, New York.

Buchanan, B., Hamilton, M.J., Edinborough, K., O'Brien, M.J. & Collard, M. (2011) A
comment on Steele's (2010) "Radiocarbon dates as data: quantitative strategies for
estimating colonization front speeds and event densities" *Journal of Archaeological*
Science, **38**, 2116-2122.

Burrows N.D., Burbidge A.A. & Fuller P.J. (2006) Evidence of altered fire regimes in the
Western Desert region of Australia. *Conservation Science Western Australia*, **5**, 272 –
284.

- Burrows, N., Ward, B. & Robinson, A. (2010) Fire regimes and tree growth in low rainfall Jarrah forest of south-west Australia. *Environmental Management*, **45**, 1332-1343.
- Chabot-Hanowell, B. & Smith, E.A. (2013) Territorial and nonterritorial routes to Power: reconciling evolutionary ecological, social agency and historicist approaches. *Archaeological Papers of the American Anthropological Association*, **22(1)**, 72-86
- Collard, M., Edinborough, K., Shennan, S. & Thomas, M.G. (2010) Radiocarbon evidence indicates that migrants introduced farming to Britain. *Journal of Archaeological Science* **37**, 866-870.
- Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A. & Krebs, P. (2009) Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. *Quaternary Science Reviews*, **28**, 435–456.
- Curr, E.M. (1886) *The Australian race*. Government Printer, Melbourne.
- Daniau, A.-L., Harrison, S.P. & Bartlein, P.J. (2010) Fire regimes during the last glacial. *Quaternary Science Reviews*, **29**, 2918-2930.
- Daniau, A.-L., Harrison, S.P. & Bartlein, P.J. *et al.* (2012) Predictability of biomass burning in response to climate changes. *Global Biogeochemical Cycles*, **26**, GB4007.
- David, B. (2002) *Landscapes, Rock-Art and the Dreaming: An Archaeology of Preunderstanding*. Leicester University Press, London.

Gammage, B. (2011) *The Biggest Estate on Earth. How Aborigines made Australia*.
Allen & Unwin, Sydney.

Goodwin, I.D., Browning, S.A. & Anderson, A.J. (2014) Climate windows for Polynesian
voyaging to New Zealand and Easter Island. *Proceedings of National Academy of
Science*, doi/10.1073/pnas.1408918111

González-Sampériz, P., Utrilla, P., Mazo, C., Valero-Garcés, B., Sopena, MC., Morellón,
M., Sebastián, M., Moreno, A. & Martínez-Bea, M. (2009) Patterns of human occupation
during the early Holocene in the Central Ebro Basin (NE Spain) in response to the 8.2ka
climatic event. *Quaternary Research*, **71**, 121-132.

Griffiths, M.L., Drysdale, R.N., Gagan, M.K., Zhao, J-X., Ayliffe, L.K., Hellstron, J.C.,
Hantoro, W.S., Frisia, S., Feng, Y-X., Cartwright, I., St Pierre, E., Fischer, M.J. &
Suwargadi, B.W. (2009) Increasing Australian-Indonesia monsoon rainfall linked to early
Holocene sea-level rise. *Nature Geoscience*, **2**, 636-639.

Haberle, S.G. & Ledru, M.P. (2001) Correlations among charcoal records of fires from
the past 16,000 years in Indonesia, Papua New Guinea, and Central and South America.
Quaternary Research, **55**, 97–104.

Haberle, S.G., Hope, G.S. & van der Kaars, S. (2001) Biomass burning in Indonesia and
Papua New Guinea: natural and human induced fire events in the fossil record.
Palaeogeography, Palaeoclimatology, Palaeoecology, **171**, 256–68.

- Hallam S.J. (1975) *Fire and hearth: a study of aboriginal usage and European usurpation in south-western Australia*. Australian Institute of Aboriginal Studies, Canberra, ACT
- Head L. (1989) Prehistoric Aboriginal Impacts on the Australian vegetation: an assessment of the evidence. *Australian Geographer*, **20**, 37–45.
- Hiscock, P. (1994) Technological responses to risk in Holocene Australia. *Journal of World Prehistory*, **8**(3), 267-292.
- Horton D. (1982) The burning question: aborigines, fire and Australian ecosystems. *Mankind*, **13**, 237–51.
- Iversen, J. (1941) Landnam i Danmarks stenalder (Land occupation in Denmark's Stone Age). *Danmarks Geologiske Undersogelse*, **66**, 1–68.
- Johnson, B.J., Miller, G.H., Fogel M.L., Magee, J.W., Gagan M.K. & Chivas, A.R. (1999) 65,000 years of vegetation change in central Australia and the Australian summer monsoon. *Science*, **284**, 1150-52.
- Jones, R. (1969) Fire-stick farming. *Australian Natural History*, **16**, 224–8.
- Kennett, D.J., Anderson, A. & Winterhalder, B. (2006) The ideal free distribution, food production and the colonisation of Oceania. *Behavioral Ecology and the Transition to Agriculture* (ed. by D.J. Kennett and B. Winterhalder), pp. 265-288. University of California Press, Berkley.

Kershaw, A.P. (1986) Climatic change and aboriginal burning in north-east Australia during the last two glacial/interglacial cycles. *Nature*, **322**, 47-49.

Long, C.J., Whitlock, C., Bartlein, P.J. & Millspaugh, S.H. (1998) A 9000-year fire history from the Oregon Coast Range, based on a high resolution charcoal study. *Canadian Journal of Forestry Research*, **28**, 774–787.

Lourandos, H. (1997) *Continent of Hunter Gatherers: New Perspectives in Australian Prehistory*. Cambridge University Press, Cambridge.

McConvell P. (1996) Backtracking to Babel: The chronology of Pama-Nyungan expansion in Australia. *Archaeology in Oceania*, **31**, 125-44.

McNiven, I.J., Couch, J., Richards, T., Dolby, N., Jacobsen, G. & Gunditj Mirring Traditional Owners Aboriginal Corporation (2012) Dating Aboriginal stonewalled fishtraps at Lake Condah, southeast Australia. *Journal of Archaeological Science*, **39**, 268-286.

MacDonald, G.M., Larsen, C.P.S., Szeicz, J.M., & Moser, K.A. (1991) The reconstruction of boreal forest fire history from lake sediments: a comparison of charcoal, pollen, sedimentological and geochemical indices. *Quaternary Science Reviews*, **10**, 53–71.

Magee, J., Miller, G.H., Spooner, N.A. & Questiaux, D. (2004) Continuous 150 k.y. monsoon record from Lake Eyre, Australia: Insolation-forcing implications and unexpected Holocene failure. *Geology*, **32(10)**, 885-888.

Marlon, J.R., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J. & Prentice, I.C. (2008) Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience*, **1**, 697-701.

Marlon, J.R., Bartlein, P.J., Danianu, A.L., Harrison, S.P. Maezumi, S.Y. & Power, M.J. (2013) Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. *Quaternary Science Reviews*, **65**, 5-25.

Miller, G.H., Fogel, M.L., Magee, J.W., Gagan, M.K., Clarke, S.J. & Johnson, B.J. (2005) Ecosystem collapse in Pleistocene Australia and a human role in megafaunal extinction. *Science*, **309**, 287-290.

Mooney, S.D., Webb, M. & Attenbrow, V. (2007) A comparison of charcoal and archaeological information to address the influences on Holocene fire activity in the Sydney Basin. *Australian Geographer*, **38**, 177-194.

Mooney, S., D., Harrison, S.D., Bartlein, P.J., Danianu, A-L., Stevenson, J., Brownlie, K.C., Buckman, S., Cupper, M., Luly, J., Black, M., Calhoun, E., D'Costa, D., Dodson, J., Haberle, S., Hope, G.S., Kershaw, P., Kenyon, C., McKenzie, M. & Williams, N. (2011) Late Quaternary fire regimes of Australasia. *Quaternary Science Reviews*, **30**, 28-46.

Moy, C.M., Seltzer, G.O., Rodbell, D.T., & Anderson, D.M. (2002) Variability of El Niño/Southern oscillation activity at millennial timescales during the Holocene epoch. *Nature*, **420**, 162-165.

Notaro, M., Wyrwoll, K-H. & Chen, G. (2011) Did Aboriginal vegetation burning impact on the Australian monsoon? *Geophysical Research Letters*, **38(11)**, L11704.

- Patterson, W.A. III, Edwards, K.J., & Maguire, D.J. (1987) Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews*, **6**, 3–23.
- Peros, M.C., Munoz, S.E., Gajewski, K., & Viau, A.E. (2010) Prehistoric demography of North America inferred from radiocarbon data. *Journal of Archaeological Science*, **37**, 656 – 664.
- Power, M.J., Marlon, J.R., Bartlein, P.J. & Harrison, S.P. (2010) Fire history and the Global Charcoal Database: a new tool for hypothesis testing and data exploration. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **291**, 52-59.
- Reeves, J.M., Barrows, T.T., Cohen, T.J., Kiem, A.S., Bostock, H.C., Fitzsimmons, K.E., Jansen, J.D., Kemp, J., Krause, C., Petherick, L., Phipps, S.J. & OZ-INTIMATE Members. (2013) Climate variability over the last 35,000 years recorded in marine and terrestrial archives in the Australian region: an OZ-INTIMATE compilation. *Quaternary Science Reviews*, **74**, 21-34.
- Rein, B., Lückge, A. & Sirocko, F. (2004) A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters*, **31**, L17211.
- Ross, J. (2013) A continent of nations: The emergence of new regionally distinct rock art styles across Australia. *Quaternary International*, **285**, 161-171.
- Sakaguchi, S., Bowman, D.M.J.S., Prior, L.D., Crisp, M.D., Linde, C.C., Tsumura, Y., & Isagi, Y. (2013) Climate, not Aboriginal landscape burning, controlled the historical demography and distribution of fire-sensitive conifer populations across Australia. *Proceedings of Royal Society B*, **280**, 20132182.

Singh, G., Kershaw, A.P. & Clark, R. (1981) Quaternary Vegetation and Fire History in Australia. *Fire in the Australian Biota* (ed. by A.M. Gill, R.H. Groves, and I.R. Noble), pp. 23-54. Australian Academy of Science, Canberra.

Shennan, S., Downey, S.D., Timpson, A., Edinborough, K., Colledge, S., Kerig, T., Manning, K., & Thomas, M.G. (2013) Regional population collapse followed initial agricultural booms in mid-Holocene Europe. *Nature Communications*, DOI: 10.1038/ncomms3486.

Smith, BD (2001) Low-level food production. *Journal of Archaeological Research*, **9**(1), 1-43.

Smith, M.A. (2005) Desert archaeology, linguistic stratigraphy, and the spread of the Western Desert language. *Desert Peoples Archaeological Perspectives* (ed. by P. Veth, M.A. Smith, and P. Hiscock), pp. 222-242. Massachusetts: Blackwell Publishing.

Smith, M.A. (2013) *The Archaeology of Australia's Deserts*. Cambridge University Press, New York.

Smith, M.A. & Ross, J. (2008) What happened at 1500-1000 BP in central Australia? Timing, impact and archaeological signatures. *The Holocene*, **18**(3), 387-396.

Smith, M.A., Williams, A.N., Turney, C.S.M. & Cupper, M. (2008) Human environment interactions in Australian drylands: Exploratory time-series analysis of archaeological records. *The Holocene*, **18**(3), 389-401.

Smith, M.A., Watchman, A. & Ross, J. (2009) Direct dating indicates a mid-Holocene age for archaic rock engravings in arid Central Australia. *Geoarchaeology*, **24**(2), 191-203.

Tindale, N.B. (1959) Ecology of primitive Aboriginal man in Australia. *Biogeography and ecology in Australia* (ed. A. Keast, R.L. Crocker and C.S. Christian), pp. 36–51. W Junk, Den Haag, Netherlands.

Ugan, A, Bright, J, & Rogers, A. (2003) When is technology worth the trouble? *Journal of Archaeological Science*, **30**, 1315-1329.

Ulm, S. (2011) Coastal foragers on southern shores: Marine resource use in northeast Australia since the late Pleistocene. *Trekking the Shore: Changing Coastlines and the Antiquity of Coastal Settlement* (ed. N.F. Bicho, J.A. Haws, and L.G. Davis), pp. 441-461. Springer, New York.

Ulm, S., (2013) ‘Complexity’ and the Australian continental narrative: Themes in the archaeology of Holocene Australia. *Quaternary International*, **285**, 182-192.

Veth, P.M, Hiscock, P. & Williams, A.N. (2011) Why the Appearance of Tulas in Australia is linked to ENSO. *Australian Archaeology*, **72**, 7-14.

Whitlock, C. & Millspaugh, S.H. (1996). Testing assumptions of fire history studies: an examination of modern charcoal accumulation in Yellowstone National Park. *The Holocene*, **6**, 7-15.

- Wilkins, D., Gouramanis, C., De Deckker, P., Fifield, L.K. & Olley, J. (2013) Holocene lake-level fluctuations in Lake Keilambete and Gnotuk, southwestern Victoria, Australia. *The Holocene*, **23**(6), 784-795.
- Williams, A.N. (2012) The use of summed radiocarbon probability distributions in archaeology: A review of methods. *Journal of Archaeological Science*, **39**, 578-589.
- Williams, AN. (2013) A new population curve for prehistoric Australia. *Proceedings of the Royal Society B*, **280**, 20130486.
- Williams, A.N., Santoro, C.M., Smith, M.A. & Latorre, C. (2008) The impact of ENSO in the Atacama desert and Australian arid zone: exploratory time-series analysis of archaeological records. *Chungara, Revista de Antropología Chilena*, **40**, 245-259.
- Williams, A.N., Ulm, S., Goodwin, I., & Smith, M. (2010) Hunter-Gatherer Response to late Holocene climatic variability in Northern and Central Australia. *Journal of Quaternary Science*, **25**(6), 831 – 838.
- Williams, A.N., Ulm, S., Cook, A.R., Langley, M.C. & Collard, M. (2013) Human refugia in Australia during the Last Glacial Maximum and Terminal Pleistocene: A geospatial analysis of the 25-12ka Australian archaeological record. *Journal of Archaeological Science*, **40**, 4612-4625.
- Williams, A.N., Ulm, S., Smith, M.A. & Reid, J. (2014) AustArch: A Database of ¹⁴C and Non-¹⁴C Ages from Archaeological Sites in Australia - Composition, Compilation and Review (Data Paper). *Internet Archaeology*, **36**, doi:10.11141/ia.36.6.

Williams, A.N., Ulm, S., Turney, C.S.M., Rohde, D. & White, G. (submitted) The Establishment of Complex Society in Prehistoric Australia: Demographic and Mobility Changes in the Late Holocene. *Plos One*.

Wroe, S., Field, J.H., Archer, M., Grayson, D.K., Price, G.J., Louys, J., Tyler Faith, J., Webb, G.E., Davidson, I. & Mooney, S.D. (2013) Climate change frames debate over the extinction of megafauna in Sahul (Pleistocene Australia-New Guinea). *Proceedings of the National Academy of Science*, **110**(36), E3369.

Wyrwoll, K-H. & Miller, G.H. (2001) Initiation of the Australian summer monsoon 14,000 years ago. *Quaternary International*, **83-85**, 119-128.

WWLLN (2014) World Wide Lightning Location Network. Available at: <http://wwlln.net/new/> accessed Nov., 2014.