

A late Holocene onset of Aboriginal burning in southeastern Australia

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ABSTRACT

The extent to which Aboriginal Australians used fire to modify their environment has been debated for decades and is generally based on charcoal and pollen records rather than landscape responses to land-use change. Here we investigate the sensitivity of *in-situ*-produced ¹⁰Be, an isotope commonly used in geomorphological contexts, to anthropogenic perturbations in the southeastern Australian Tablelands. Comparing ¹⁰Be-derived erosion rates from fluvial sediment (8.7 ± 0.9 mm k.y.⁻¹; 1 standard error, SE; $n = 11$) and rock outcrops (5.3 ± 1.4 mm k.y.⁻¹; 1 SE; $n = 6$) confirms that landscape lowering rates integrating over 10^4 – 10^5 yr are consistent with rates previously derived from studies integrating over 10^4 to $>10^7$ yr. We then model an expected ¹⁰Be inventory in fluvial sediment if background erosion rates were perturbed by a low-intensity, high-frequency Aboriginal burning regime. When we run the model using the average erosion rate derived from ¹⁰Be in fluvial sediment (8.7 mm k.y.⁻¹), measured and modeled ¹⁰Be concentrations overlap between ca. 3 ka and 1 ka. Our modeling is consistent with intensified Aboriginal use of fire in the late Holocene, a time when Aboriginal population growth is widely recognized.

INTRODUCTION

The arrival of humans to unpopulated or sparsely populated lands can lead to permanent vegetation shifts, increased erosion, and extended wildfire burning seasons and can be facilitated by small populations of humans soon after arrival, especially if fire is used (Archibald et al., 2013; Burney et al., 1994; Coltorti et al., 2010; Dugmore et al., 2000, 2005; McWethy et al., 2010; Sandgren and Fredskild, 1991). In Australia, small Aboriginal populations were established around the continent by ca. 50 ka (Olley et al., 2006; Roberts et al., 1994; Turney et al., 2001), leading some to argue that Aboriginal burning rapidly altered the Australian environment upon arrival (Jones, 1969; Miller et al., 2005; Rule et al., 2012; Turney et al., 2001). The Australian paleohydrological record, however, suggests that aridification, not human activity, led to environmental change at 45 ka (Cohen et al., 2015). Increased water delivery to wetlands, a result of permanent deforestation, is only evident in eastern Australia since 19th century land clearance by Europeans (Woodward et al., 2014).

Across Australia, charcoal records appear to be unaffected by Pleistocene–early Holocene human land use; they are linked, instead, to climatic variation (Mooney et al., 2011). In eastern New South Wales, increased charcoal at 5.5 ka is attributed to a mid-Holocene strengthening of the El Niño–Southern Oscillation (ENSO; Black et al., 2007; Shulmeister, 1999). Late Holocene

charcoal abundances decreased at the same time that Aboriginal burning regimes are thought to have become commonplace because the low-intensity, high-frequency burns consumed less biomass (Black et al., 2007; Lourandos, 1980). Despite these recent findings, questions regarding the effects of Aboriginal burning on the Australian environment and the timing of the onset of this burning will remain unresolved without independent data sets.

Cosmogenic ¹⁰Be serves as a proxy for the residence time of rock and sediment near Earth's surface and can be used to infer erosion rates integrating over 10^4 – 10^5 yr time scales (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996; Nishiizumi et al., 1986). We use ¹⁰Be to provide a new perspective on Aboriginal land use in the southeastern Australian Tablelands of eastern New South Wales by testing for changes in background erosion rates resulting from the onset of Aboriginal fire regimes. In doing so, we present a new approach of applying ¹⁰Be in a geoarchaeological context that can be adapted to other landscapes with long histories of human occupation, thereby using interpretations of regional land use to supplement site-specific archaeological data.

SOUTHEASTERN AUSTRALIAN TABLELANDS

Our study focuses on the central southeastern Australian Tablelands, a $>11,250$ km² low-relief terrain that straddles part of the Great Dividing Range at 500–1000 m above sea level (Fig. 1). Grasslands were prevalent on the Tablelands in

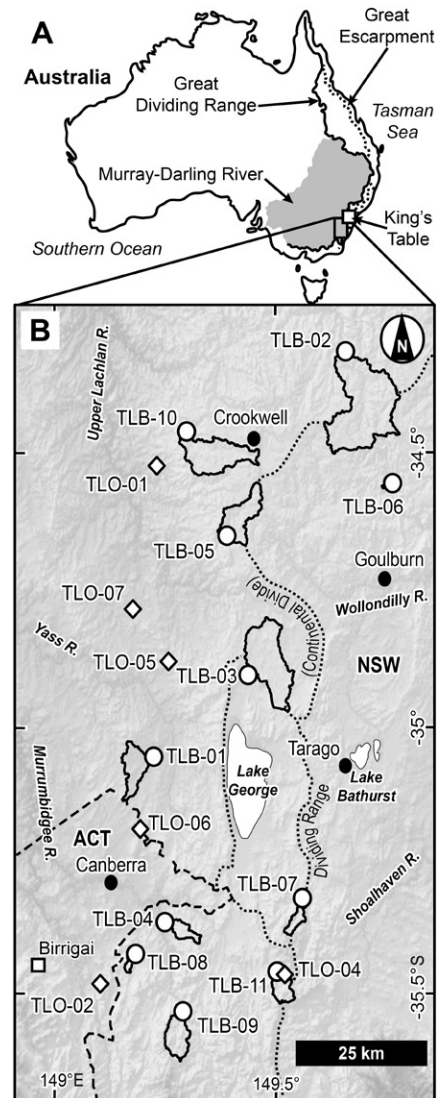


Figure 1. A: Key physiographical and landscape features of the Tablelands region, southeastern Australia. White square shows the location of the Kings Table Rock Shelter (Stockton and Holland, 1974). B: Sampling locations of bedrock outcrops (diamonds) and fluvial sediment (white circles). Cities (black circles) within New South Wales (NSW) and the Australian Capital Territory (ACT) are labeled for reference. White square shows the location of the Birrigai Rock Shelter (Flood et al., 1987). Sample coordinates are provided in Table DR2 (see footnote 1). Base map is the World Shaded Relief coverage (Esri; http://services.arcgisonline.com/ArcGIS/rest/services/World_Shaded_Relief/MapServer).

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the Pleistocene, and open eucalyptus woodlands spread into the Tablelands during the Holocene, although forest understories remained open and grassy (Dodson, 1986). Radiometric dating and sediment mass balance studies (Bishop, 1985; Bishop and Goldrick, 2000) show that the Tablelands have been eroding at average rates of at least 3–8 mm k.y.⁻¹ since 30–20 Ma; rates of 5–10 mm k.y.⁻¹ are more likely (Bishop, 1985).

Evidence for human activity in the Tablelands region dates to ca. 21 ka at the Birrigai Rock Shelter near Canberra and at the King's Table Rock Shelter in the nearby Blue Mountains (Fig. 1; Flood et al., 1987; Stockton and Holland, 1974), but the shelters do not preserve continuous histories of habitation. Other archaeological records suggest that, except for a brief period ca. 14–12 ka, the Tablelands region was permanently occupied only in the late Holocene (Bowdler, 1981; Flood et al., 1987; Stockton and Holland, 1974). Such inferences are consistent with measures of Australian population growth and interpretations of the Blue Mountains charcoal record (Black et al., 2007; Bowdler, 1981; Lourandos, 1980).

Anthropogenic fire has undoubtedly been used to alter Australian vegetation (Bowman, 1998). Specific details of traditional Aboriginal fire regimes and knowledge of when they were introduced to the Tablelands were lost when local Aboriginal communities were overrun by Europeans and their grazing stations early in the 19th century. Nevertheless, it seems that Aboriginal fires in the Tablelands were likely set no more than 1 yr in every 5 yr, in small, mosaicked patches (Bowman, 1998; Gott, 2005). Low-intensity fires on areas of the modern Tablelands that are relatively unaffected by European land use increase sediment yields by 30–50× (Prosser, 1990), providing an estimate of the magnitude of landscape response to low-intensity Aboriginal burns. If fire was used on the Tablelands by the first occupants ca. 21 ka, the evidence for anthropogenic fire regimes seems to be overshadowed in the charcoal record by naturally occurring fires linked to climatic variations. For this reason, we look to the geomorphological and isotopic record for additional insight into Aboriginal burning in order to see if and how such burning affected the rate of erosion.

METHODS

If long-term average erosion rates are consistently low (<10 mm k.y.⁻¹), the effects of low-intensity, high-frequency Aboriginal burning on ¹⁰Be concentrations in fluvial sediment will be detectable because ¹⁰Be concentrations at the landscape surface will decrease as soil is stripped by intensified erosion. We derived erosion rates integrating over 10⁴–10⁵ yr from ¹⁰Be measured in fluvial sediment samples collected in active streambeds throughout the Tablelands

($n = 11$; 1–190 km²) and from rock outcrops ($n = 6$; Fig. 1). We compared ¹⁰Be-derived erosion rates to those estimated by radiometric and soil production studies (Bishop, 1985; Bishop and Goldrick, 2000; Heimsath et al., 2001; Suresh et al., 2013) to assess the consistency of erosion rates averaged over different time scales. The production rate of ¹⁰Be through time and as a function of depth in rock or soil is well understood (Lal, 1991), enabling us to model ¹⁰Be inventories in fluvial sediment under different Aboriginal fire regimes, given background erosion rates of 5–10 mm k.y.⁻¹. Model results depend on when Aboriginal landscape burning is introduced, perturbing erosion and changing ¹⁰Be inventories. We use previous studies (e.g., Heimsath et al., 2001; Suresh et al., 2013) to verify the assumption that ¹⁰Be concentrations in soils and bedrock had reached secular equilibrium with regard to erosion and production prior to the onset of Aboriginal burning. We then compare predicted ¹⁰Be concentrations under a range of background erosion rates with measured ¹⁰Be concentrations to assess the timing of the onset and continued use of Aboriginal burning. Samples were processed and beryllium was isolated at the University of Vermont (USA). ¹⁰Be/⁹Be ratios were measured using accelerator mass spectrometry at the Scottish Universities Environmental Research Centre (East Kilbride, UK; Xu et al., 2015). Erosion rates were derived from measured ¹⁰Be concentrations using the CRONUS erosion rate calculator (<http://hess.ess.washington.edu>; Balco et al., 2008). Details of the land-use model, sample collection strategy, and laboratory methods are provided in the GSA Data Repository¹.

TABLELANDS LANDSCAPE DYNAMICS

The similarity between the average ¹⁰Be-derived erosion rates from fluvial sediment (8.7 ± 0.9 mm k.y.⁻¹, mean \pm SE; $n = 11$) and rock outcrops (5.3 ± 1.4 mm k.y.⁻¹; $n = 6$) indicates that the Tablelands continue to maintain a low average rate of surface lowering over millennial time scales (7.5 ± 0.9 mm k.y.⁻¹, mean of all samples \pm SE; Tables DR1 and DR2 in the Data Repository). ¹⁰Be-derived erosion rates integrate over the time required to erode through one cosmic ray attenuation length of Earth surface material (160 g cm⁻²; Balco et al., 2008), which is ~107 cm for the source of stream sediment (i.e., 100 cm of soil, $\rho = 1.4$ g cm⁻³; ~7 cm of bedrock, $\rho = 2.7$ g cm⁻³); the attenuation length is ~60 cm for bedrock outcrops. Thus, the integration times for erosion rates in our data set range from 46

to 230 k.y., implying that the average ¹⁰Be erosion rate of all samples (7.5 mm k.y.⁻¹) is consistent with the 5–10 mm k.y.⁻¹ geological erosion rates integrating over more than 20 m.y. (Bishop, 1985; Bishop and Goldrick, 2000). This finding confirms that average surface lowering rates in the Tablelands persisted from the late Pleistocene into the Holocene. We thus infer that neither Aboriginal burning nor strengthening ENSO climate patterns (Bowman, 1998; Shulmeister, 1999) were sufficiently intense or effective over a large enough proportion of the ¹⁰Be integration time to alter background erosion rates. Sediment fluxes calculated from ¹⁰Be-derived erosion rates (Fig. DR2; Table DR2) are lower than those predicted for a disturbed post-European Tablelands landscape (Wasson, 1994), emphasizing that the ¹⁰Be-derived erosion rates for ungullied catchments, as in this study (see Sample Collection Strategy in the Data Repository), are unaffected by modern land use (e.g., Hewawasam et al., 2003; Reusser et al., 2015).

INTENSIFICATION OF ABORIGINAL BURNING

Although Aboriginal burning did not alter background erosion rates, we can assess the timing of the onset of Aboriginal burning by comparing measured ¹⁰Be concentrations in fluvial sediment to those predicted by our land-use model. Our modeling results yield ¹⁰Be concentrations we expect to measure in fluvial sediment had Aboriginal fires been set 1 yr in every 5 yr, increasing background erosion rates of 5–10 mm k.y.⁻¹ by 30× or by 50× (Fig. 2). The 5–10 mm k.y.⁻¹ geological erosion rate range sets limits on what we consider to be plausible interpretations of land-use chronologies, and because the Tablelands is currently a soil-mantled landscape (Suresh et al., 2013), we only consider model results that show ¹⁰Be in fluvial sediment being derived from soil-mantled rather than bedrock landscapes (Fig. 2).

Our modeling shows that the measured ¹⁰Be concentrations in fluvial sediment could result from various human land-use histories (Fig. 2). For example, the ¹⁰Be measured in fluvial sediment could be generated by 21 k.y. of Aboriginal burning with a background erosion rate of >5 mm k.y.⁻¹ if burning increased erosion rates by 30× (A, Fig. 2); all soil would have been eroded by the Holocene if burning increased erosion rates by 50× (Fig. 2). These scenarios are unlikely because there is evidence for continuous occupation only since the late Holocene (Flood et al., 1987; Stockton and Holland, 1974). European burning for ~200 yr (B, Fig. 2) is unlikely to yield the measured ¹⁰Be because European burns were more intense and less frequent than those in our model (Bowman, 1998), meaning that predicted surficial ¹⁰Be concentrations would be significantly less than that measured, even after only ~200 yr.

¹GSA Data Repository item 2016034, supplementary Figures DR1–DR4, land-use model details, sample collection strategy, laboratory methods, and data tables, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

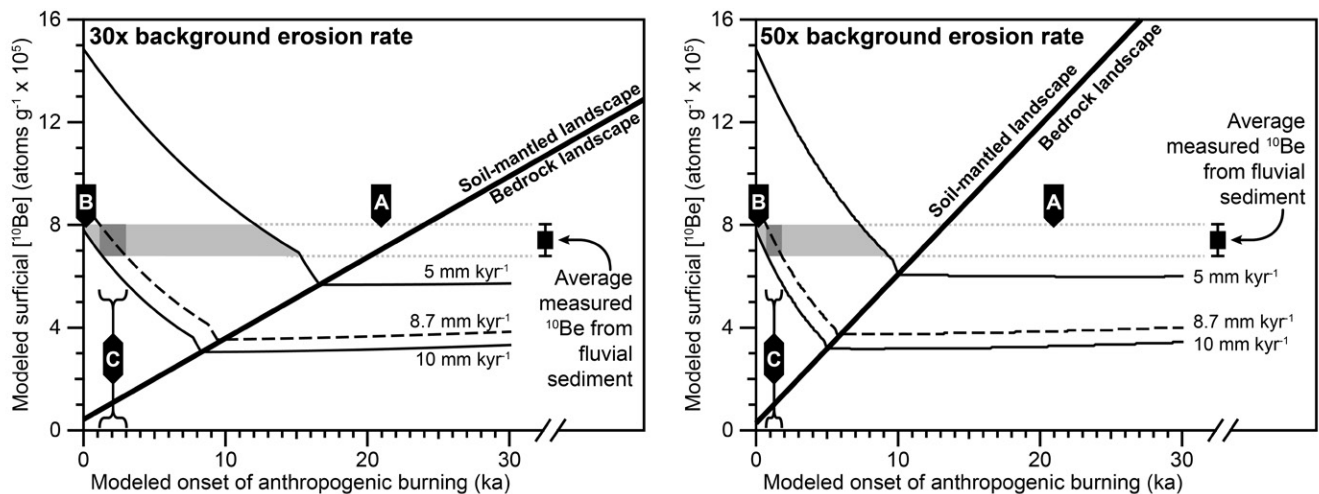


Figure 2. Results from a low-intensity, high-frequency Aboriginal burning regime model in which the background erosion rates are increased 30x or 50x for 1 yr out of every 5 yr (left and right panels, respectively). Isolines connect model-derived expected ^{10}Be concentrations for the land surface for various specific background erosion rates. Only solutions to the model in which fluvial sediment is derived from soil, not bedrock, are considered. Solid gray bar and black box and whisker icon are the average and standard error of measured ^{10}Be inventories from stream catchments ($n = 11$). Dashed isobar reflects expected ^{10}Be concentrations given a background erosion rate of 8.7 mm k.y.^{-1} , derived from ^{10}Be measured in fluvial sediment. A—oldest archaeological evidence for human habitation in the Tablelands region of southeastern Australia (Flood et al., 1987; Stockton and Holland, 1974); B—arrival of Europeans to Australia; C—time of intensive burning given overlap between expected and measured ^{10}Be concentrations from fluvial sediment given the 8.7 mm k.y.^{-1} background erosion rate.

The late Holocene continuous human occupation of the Tablelands represents only a small proportion of the ^{10}Be integration time, not long enough to increase ^{10}Be -derived erosion rates above the long-term limit of 10 mm k.y.^{-1} . We run the model using the average ^{10}Be erosion rate derived from fluvial sediment (8.7 mm k.y.^{-1}) to determine when continuous Aboriginal burning was likely introduced to the Tablelands, thus yielding the average measured ^{10}Be concentration in fluvial sediment (Fig. 2). Measured and modeled ^{10}Be inventories overlap ca. 3–1 ka (C, Fig. 2), consistent with Aboriginal Australians in the Tablelands using low-intensity, high-frequency burns in the late Holocene. A ca. 2–1 ka onset of the Aboriginal burning regime is possible if burning increases background erosion rates in the model by 50x (Prosser, 1990), instead of by 30x (Fig. 2).

We recognize that climate change associated with a mid-Holocene strengthening of the ENSO could have perturbed erosion in the Tablelands, thereby affecting the ^{10}Be concentration in fluvial sediment. However, our model is specifically set up to simulate the magnitude and frequency of anthropogenic land use, and our interpretations are consistent with previous studies, which concluded that the late Holocene was an important time for Aboriginal population growth in eastern New South Wales (Black et al., 2007; Bowdler, 1981; Lourandos, 1980). Furthermore, the late Holocene onset of burning inferred from our model is consistent with the conclusion of Black et al. (2007) that low abundances of charcoal in the sedimentary record reflect continuous low-intensity burns initiated in the late Holocene.

CONCLUSIONS

Erosion rates derived from ^{10}Be concentrations in fluvial sediment and bedrock outcrops indicate that the Tablelands landscape continues to have the same average, slow surface-lowering rates over millennial time scales as have been inferred for time scales of tens of millions of years. Aboriginal burning regimes were not sufficiently intense or long lasting to alter background ^{10}Be -derived erosion rates. Our understanding of Aboriginal fire regimes in the Tablelands and *in situ* ^{10}Be production allows us to identify the late Holocene as the most likely time of the onset of burning in the Tablelands. This is not to say that Aboriginal Australians never used fire to alter landscapes prior to the late Holocene, but that Aboriginal burns prior to this time were too infrequent, localized, or low impact to have altered erosion rates or modulated ^{10}Be inventories.

Our study is the first to assess the timing of intensified Aboriginal burning in Australia using a geomorphological and isotopic approach. That our conclusions are similar to those of recent archaeological, charcoal-based, and hydrological investigations of anthropogenic land use confirms the robustness of our modeling approach and the applicability of ^{10}Be to geoarchaeology. Applying ^{10}Be in this way provides important regional cross-checks for inferences of indigenous land use based on other site-specific archaeological investigations, thus supplementing conclusions drawn about humankind's collective prehistorical impact on the physical landscape. Our application of ^{10}Be in a landscape affected recently by human activity provides a glimpse of how ^{10}Be might be useful for those working in landscapes occupied by humans over longer durations.

ACKNOWLEDGMENTS

This research was funded by Macquarie University Postgraduate Research Fund and International Research Excellence Scholarships and a University of Glasgow International Ph.D. Research Studentship. We thank Veronica Sosa-González, Lee Corbett, Tom Neilson, and Meredith Orr for field and laboratory assistance, and Taylor Schildgen and two anonymous reviewers for thoughtful feedback.

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Manuscript received 12 August 2015

Revised manuscript received 6 December 2015

Manuscript accepted 8 December 2015

Printed in USA

Geology

A late Holocene onset of Aboriginal burning in southeastern Australia

Eric W. Portenga, Dylan H. Rood, Paul Bishop and Paul R. Bierman

Geology published online 7 January 2016;
doi: 10.1130/G37257.1

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