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Reconstructing the dynamics of ancient human populations from radiocarbon dates: 10 000 years of population growth in Australia

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Measuring trends in the size of prehistoric populations is fundamental to our understanding of the demography of ancient people and their responses to environmental change. Archaeologists commonly use the temporal distribution of radiocarbon dates to reconstruct population trends, but this can give a false picture of population growth because of the loss of evidence from older sites. We demonstrate a method for quantifying this bias, and we use it to test for population growth through the Holocene of Australia. We used model simulations to show how turnover of site occupation across an archaeological landscape, interacting with erasure of evidence at abandoned sites, can create an increase in apparent site occupation towards the present when occupation density is actually constant. By estimating the probabilities of abandonment and erasure from archaeological data, we then used the model to show that this effect does not account for the observed increase in occupation through the Holocene in Australia. This is best explained by population growth, which was low for the first part of the Holocene but accelerated about 5000 years ago. Our results provide new evidence for the dynamism of non-agricultural populations through the Holocene.

Keywords: prehistory; human population growth; intensification; demography; Holocene

1. INTRODUCTION

As databases of radiocarbon dates have grown, archaeologists have increasingly used the distributions of those dates through time to reconstruct the dynamics of prehistoric human populations [1,2]. This assumes that the size of an ancient population is indicated by the quantity of evidence—especially, the number of dated occupation sites—that it left behind. Frequency distributions of radiocarbon dates have been used to infer trends in the population of Europe through the last glacial maximum [3], of Siberia during the Palaeolithic [4], and of tropical Australia over the last 40 000 years [5], among many other examples.

However, there is a serious problem with this methodology. The longer it is since something happened, the greater is the probability that evidence of that event will have disappeared. Younger events, therefore, tend to be over-represented in compilations of dates. A constant probability of erasure of evidence through time will produce an exponential increase in the number of dated events towards the present, mimicking population growth [2]. This ‘pull of the recent’ [6] may explain why a pattern of increase towards the present is common in many compilations of dates, not just of archaeological sites but also of phenomena such as volcanic deposits, fossil occurrences and ages of coins in circulation [2,6–10].

Surovell *et al.* [7] suggested that preservation bias could be measured and removed from archaeological databases by comparing the age-distributions of dates on archaeological sites with those of dates on relevant geological contexts. They provided two examples of how to do this. First, they used the observed global age-distribution of volcanic deposits as a proxy to measure the preservation bias in the archaeological record. Volcanic deposits are known (from atmospheric records captured in the Greenland ice sheet) to have been produced at a constant rate over the last 40 000 years, but the distribution of radiocarbon dates on such deposits is skewed towards the present. They modelled this effect, and used the model as a filter to remove the same effect from radiocarbon dates on archaeological sites. Second, counts of dates on open archaeological sites were divided by counts of dates on alluvial sediments from the same region.

Both approaches correct the age-distribution of sites by removing the effects of geomorphic processes that progressively reduce the availability of substrates in which archaeological material is preserved. But for these procedures to eliminate preservation bias, the strength of the taphonomic effect must be equal for archaeological material and related geological surfaces. For instance, if the evidence dated by archaeologists is more easily erased than the material used to date geological substrates, the taphonomic effect on archaeology will be underestimated. Because it is usually not possible to measure the strength of preservation

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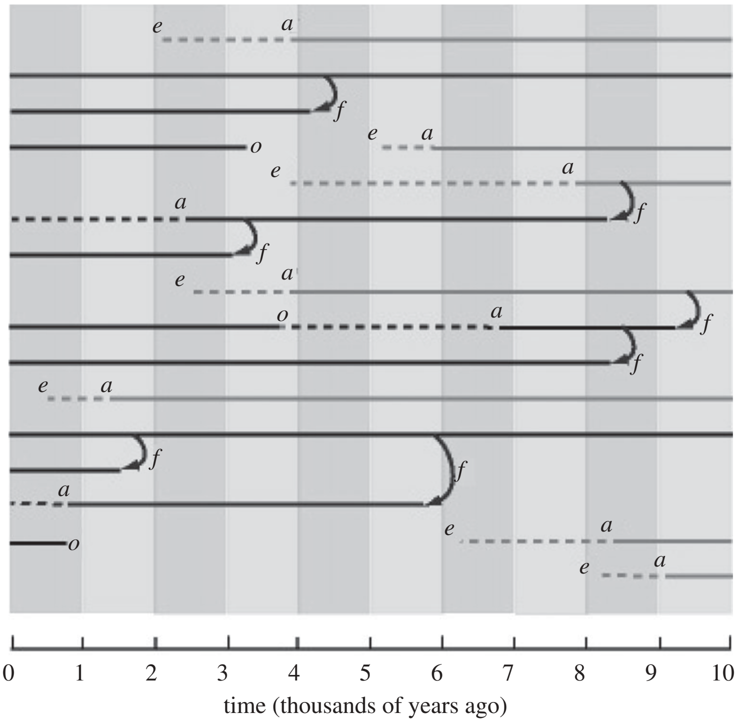

number of sites occupied	9	9	9	10	9	8	8	9	10	9	9
number of occupied sites with surviving evidence	9	9	8	9	6	5	4	5	3	3	2

Figure 1. Illustration of the structure of the model used to simulate effects of age-dependent preservation bias and population growth on the distribution of radiocarbon dates through time. Occupied sites are indicated by solid horizontal lines. Sites may be abandoned (*a*), after which evidence of occupation may persist (dashed line) for some time until it is erased (*e*). Previously occupied sites may be re-occupied (*o*), and new sites founded (*f*) from existing sites. Sites that have been abandoned and erased before the present are invisible, so that while turnover maintains a near-constant number of occupied sites, the number of known sites increases towards the present.

bias directly, some uncertainty over archaeological reconstructions of population trends will remain.

An alternative approach is to base demographic reconstructions on durable archaeological sites, for which preservation bias is assumed to be small on the timescales of interest. This is usually done by restricting analysis to rockshelters and caves, because they are less subject to destructive geomorphological processes than are open-air sites [5,7]. However, there can still be temporal bias affecting occupation data for rockshelters. Rockshelter occupations are most likely to be found, excavated and dated if there is surface exposure of artefacts. Surface exposure is maintained by occupation, but once a site is abandoned, gradual degradation of evidence at the surface or covering by sediments is inevitable. Sites that have been abandoned (and not re-occupied) for long periods are thus more likely to be archeologically invisible than are recently occupied sites, even if their gross geological contexts remain stable. This bias towards observation of recently occupied sites could create the appearance of population growth in a system where there is a turnover of site occupation with occasional abandonment of sites being compensated by the founding of new sites and re-occupation of old ones to produce a shifting pattern of habitation across a landscape of potential occupation sites. The loss of visibility of long-abandoned sites would produce the appearance of an increase in number of occupations through time, even when the actual rates of abandonment of old sites and founding of new ones balance out to produce a long-term steady state, as illustrated in figure 1.

In this study, we explored the situation depicted in figure 1 and compared it with reality, using a large compilation of radiocarbon dates on occupation of rockshelters across mainland Australia through the last 10 000 years. Many previous studies have used the rockshelter records of particular regions of mainland Australia to infer that population density increased through the Holocene, especially over the last 4000 years or so [5,11–23]. We tested whether the observed increase in number of dates was more consistent with a steady state subject to preservation bias, or a true increase in the number of sites occupied through time. Our approach was to develop a model to describe the interaction of the processes of site founding, abandonment and post-abandonment erasure of evidence of occupation, so that we could use simulations to show how these processes interact to create the appearance of growth in numbers of archaeologically visible sites. We then estimated key parameters in the model, to test whether the taphonomic effect was strong enough to be the sole explanation of the apparent temporal increase in occupation of rockshelters in Australia, or whether population growth is required to account for this.

2. METHODS

We set up an individual-based discrete time stochastic simulation of the fates of potential occupation sites. The structure of the simulation is represented in figure 1. It contains the basic processes that generate turnover of occupation across an archaeological landscape, overlain by the erasure of archaeological evidence through time, and shows how these processes affect the number of sites of different ages that are discoverable in the present.

For each site in the simulation, four probabilistic events were possible in each 1000 year period: (i) an occupied site might be *abandoned*, with probability *a*; (ii) a site that had already been abandoned might have evidence of previous occupation *erased*, with probability *e*; (iii) a site that had been abandoned might be *re-occupied*, with probability *o*; and (iv) an occupied site might be responsible for the *foundation* of new sites, with probability *f*.

Simulations were run on a site-by-site basis (each site representing an individual) and began with an occupied site at time zero. The simulation then stepped through ten 1000 year intervals to the present, at each step running through the following operations:

- checking whether the site was occupied at the beginning of the interval;
- if it was occupied, finding if it was abandoned during that interval (with probability *a*; a Monte Carlo procedure was used to find the outcomes of probabilistic processes affecting sites);
- if it was not occupied, finding if it was re-occupied (*o*) during the interval;
- if it remained unoccupied, finding if evidence of previous occupation was erased (*e*); and
- if it was occupied and not abandoned, finding the number of new sites that it founded (production of new sites followed a Poisson distribution, which is discrete and non-negative, meaning that the number of sites founded could only be 0, 1, 2, etc; the probability of founding was set as the mean/variance ratio of the Poisson distribution and was therefore a fraction).

After running through a complete history for the first site, the simulation followed any daughter sites founded by it, and continued by following any further generations of sites until all descendant sites had been evaluated. This complete procedure constituted a single iteration. Further iterations were begun by establishing additional occupied sites at time zero, and following them (and their descendant sites) to completion. At the end of a simulation (consisting of 10 000 iterations, each starting with a single occupied site), we tallied the total number of sites occupied at each time interval and for which evidence survived to the present—i.e. that were still occupied, or that had been abandoned but for which evidence of past occupation had not yet been removed by the *e* parameter. The simulation was written and run in the open source R language (www.r-project.org; see the electronic supplementary material for R code).

For comparison of the simulation results with an observed record, we compiled a database of radiocarbon dates on rockshelters from across mainland Australia from a search of the published literature. The database (available as the electronic supplementary material) contains 822 dates, calibrated using CalPal [24,25], on 267 rockshelters with occupation dates within the last 10 000 years. It was compiled independently of existing databases of dates on Australian archaeological sites, which are regionally restricted (the AustArch1 database for arid Australia [26], and the index of dates for Queensland [27]), but includes most rockshelter sites contained in them.

3. RESULTS

A demographic steady state can be simulated with our model by setting the foundation and re-occupation rates at levels that balance the abandonment rate. We predicted that in such a steady state, the effects of turnover of sites, together with erasure of evidence of past occupation, would generate the appearance of increasing occupation towards the present. This could be amplified in two distinct ways: (i) increasing turnover among sites, by increasing the abandonment rate *a* while increasing the re-occupation and founding rates to maintain the balance of loss and gains of occupied sites; and (ii) raising the erasure rate *e*, so that more evidence of earlier occupation is lost for a given degree of turnover.

We experimented with a wide range of parameter combinations to test these predictions, as illustrated by a sampling of outputs in figure 2. If the erasure rate *e* was set to zero (so that there is no loss of evidence of occupation) in a steady-state system, the model could not produce the appearance of increased occupation through time at any level of site turnover (figure 2*a*). With a non-zero erasure rate, the model did show such an increase in occupation evidence towards the present, and increasing the level of turnover amplified that effect (figure 2*b*). Increasing the value of the erasure rate *e* while holding turnover constant had a similar effect (figure 2*c*). The effect of combining high turnover with high erasure rates was to modify the shape of the relationship between occupation evidence and time, making it more curvilinear by introducing an especially steep increase in the most recent intervals.

Having observed the nature of the effects of site turnover and erasure of evidence in a steady-state system, we experimented with increases in the founding rate *f* to simulate true population growth. This produced a smooth curvilinear increase in evidence of occupation (figure 2*d*). The distribution of dates through time was more strongly affected by changes in the foundation rate than by changes in the abandonment and erasure rates.

It is possible to estimate two parameters of the model—the abandonment rate *a* and the erasure rate *e*—from empirical data on occupation of rockshelters. Abandonment can be directly determined from stratified and dated excavations of occupation sites, and is indicated by levels without artefacts overlying levels with artefacts. Several regional archaeological summaries provide information on the pattern and timing of occupation of sites through time. We combined data from the following regional compilations in this analysis: Sydney region (upper Mangrove Ck) [20]; Kimberley region [28]; Southeast Queensland [16]; Southeast Cape York peninsula [29]; West Arnhem Land [30] and Central Queensland [17].

Abandonment should be underestimated, because the existence of some abandoned sites is unknown owing to erasure of evidence. The magnitude of this underestimation should be a function of age, because long-abandoned sites are more likely to be missing from the record.

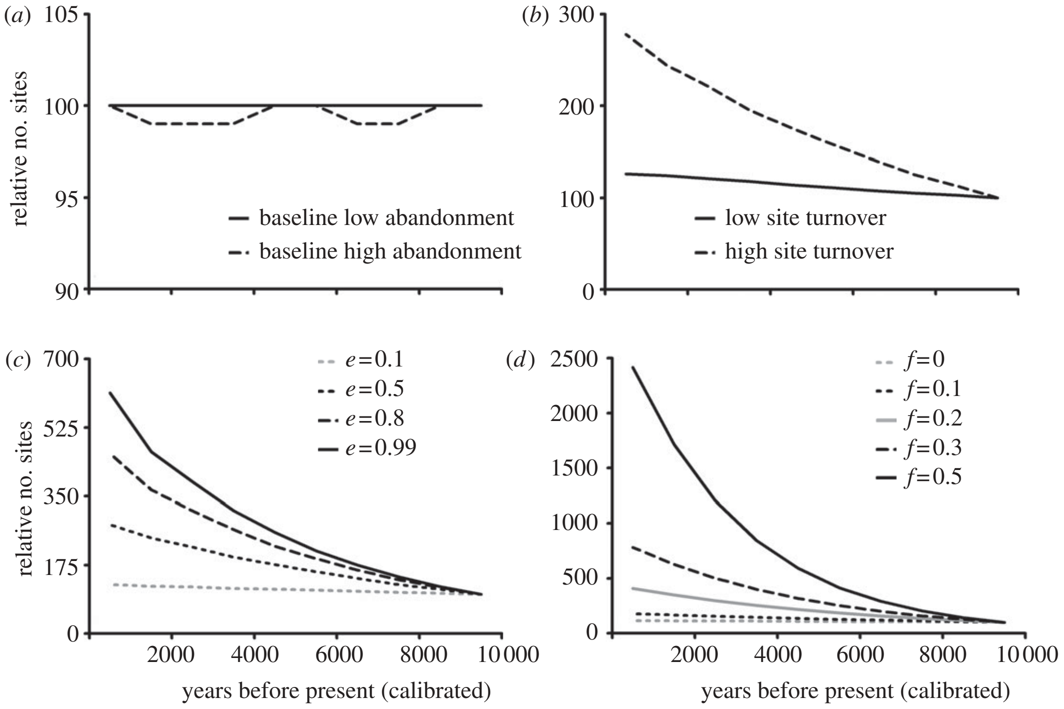

Figure 2. Representative results of simulation experiments, showing the distribution of number of sites known, from evidence that has survived to the present, to have been occupied through successive 000 year intervals over the last 10 000 years. (*a*) Temporal distribution of occupation evidence in a steady-state system with zero erasure of evidence, comparing series with low (solid line) versus high (dashed line) turnover. (*b*) Effects of site turnover on the distribution of evidence through time, when erasure of evidence is non-zero. (*c*) Effect of varying erasure rate in scenarios with constant turnover. (*d*) Effect of varying the foundation rate, while holding other rates constant. Results for each simulation were standardized to 100 sites in the first time interval. The parameter values used in these simulations are provided as electronic supplementary material.

However, an estimate of the true rate of abandonment (assuming that it is a constant) can be obtained by regressing the observed abandonment rate against time before the present. The intercept of this regression at time zero is an estimate of the unbiased abandonment rate *a*, because with zero time there can have been no loss of evidence. The slope of the regression of observed abandonment rate on time measures the rate at which evidence on sites that have been abandoned is removed from the record (assuming constant abandonment and erasure rates), and therefore provides an estimate of *e*. Figure 3 shows that abandonment was more likely to be detected in the recent past, and a weighted logistic regression fitted to these data gave estimates of $a = 0.046$ and $e = 0.191$. That is, the empirical evidence is that rockshelters were rarely abandoned, but when they were, evidence of former occupation was lost from the archaeological record quite quickly on millennial timescales.

These two parameter estimates allowed us to check whether the increase in occupation evidence through time in our full radiocarbon database could reasonably have been produced solely by the observed rate of abandonment of sites interacting with the observed rate of erasure of evidence in a steady-state system. That model produced a poor fit to the observed data ($R^2 = -30.3$), and the fit was improved only slightly by raising the abandonment and re-occupation rates to generate higher turnover, and the erasure rate to generate more rapid loss of evidence (figure 4). As a final step, we experimented with different values of population growth in combination with the empirical values for abandonment ($a = 0.05$) and erasure ($e = 0.2$) to improve the fit to the observed pattern of increase of occupation evidence. A good match was provided by a foundation rate of 0.38. However, the best fit of all ($R^2 = 97.3$), obtained iteratively by testing different values of the foundation

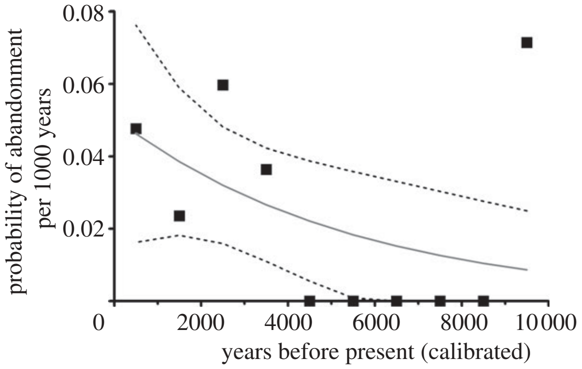

Figure 3. The relationship between time and the directly observed rate of abandonment of rockshelter occupations: the rate of abandonment appears to increase towards the present, presumably because of loss of evidence from long-abandoned sites. Data are from a total of 142 rockshelters from six regions (see text for locations and references). The fit (with 95% confidence limits) is from a logistic regression, weighted by sample size. Sample size increases from 15 in the earliest interval to 118 sites in the most recent. The outlier to the right of the curve has only a small influence on the regression, being due to a single abandonment in a sample of 15 rockshelters dated to that interval.

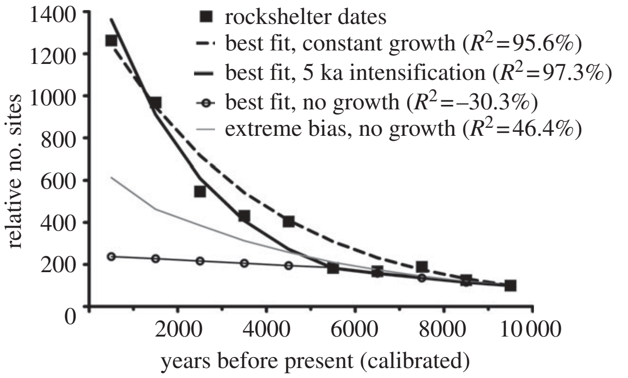

Figure 4. Comparison of simulation outputs with the observed distribution of number of occupied rockshelters (as determined by the presence of at least one radiocarbon date in a given time interval) in successive 000 year intervals over the last 10 000 years for mainland Australia. Results for each simulation were standardized to 100 sites in the first time interval. Goodness of fit is indicated by R^2, which measured the deviation between the empirical data and the model curve. The 'best fit, no growth' simulation uses the empirically estimated values of ($a = 0.05$) and ($e = 0.2$) in a steady-state system (i.e. no population growth) to estimate the magnitude of the preservation bias introduced by estimated turnover of site occupation and erasure of evidence. The 'extreme bias, no growth' applies very high values for turnover and erasure in a steady-state system, to find the closest fit to observation obtainable without assuming population growth. The 'best fit, constant growth' model uses the estimated values of ($a = 0.05$) and ($e = 0.2$), with the growth rate tuned to the value ($f = 0.38$) that gives the best fit to the observed distribution from a single combination of parameter values. The 'best fit, 5000 intensification' model improves that fit further by allowing a change in f, from 0.2 to 0.6 in the 6000–5000 year interval.

rate at different times, was given when the foundation rate was low ($f = 0.2$) for the first 4000 years of the Holocene, and was then increased to 0.6 at 5000 years and sustained at that level for the rest of the Holocene.

4. DISCUSSION

Our results show that shifting site occupation across an archaeological landscape, together with the gradual loss of evidence of occupation at abandoned sites, can produce the appearance of increasing occupation towards the present when the true occupation density is constant. This adds to analytical demonstrations of a 'pull of the recent' in archaeological datasets [2], and shows that this pull can be exerted even when the geological context of occupation is stable. Making the process explicit in a model allowed us to experiment with different combinations of turnover of occupation, erasure of evidence and population growth, and test their effects on the temporal distribution of observed occupations. For rockshelter occupations across mainland Australia, the rates of site turnover and erasure of evidence that would be required to produce the observed distribution of dates are implausibly high. However, a moderate rate of foundation of new from existing sites—representing population growth, which mostly occurred during the last few thousand years—produces an excellent fit to the observed distribution of radiocarbon dates.

The observation of Holocene population growth is a crucial piece of evidence in Australian prehistory. Beginning with Lourandos [13,14], many archaeologists have argued that Aboriginal society was transformed in the Mid-Holocene in a process of 'intensification'. This involved the development of more sedentary ways of living, increased social complexity and trade, various technological advances and development of more sophisticated systems of resource use. Population growth is viewed both as a cause and an effect of these changes. Intensification and population growth in Australia have close parallels to the social and demographic changes that accompanied the development of agriculture in other parts of the world. Nonetheless, Australians continued to live primarily as foragers, without completing the transition to farming. Australian prehistory, therefore, strengthens the view that the development of closer settlement was a widespread and fundamental response to Holocene environments among foraging and hunting peoples, which in some places led to the development of agriculture but was not primarily a result of the transition to agriculture [31]. However, uncertainty over the interpretation of the archaeological evidence has led some Australian archaeologists to doubt that there was an increase in the Australian population through the Holocene, and therefore to reject the intensification model [32–34]. Our analysis supports the view that population increase in Holocene Australia was real, with two phases: slow or negligible before 5000 years ago, and faster since then.

What caused this growth? One possibility is that it was a response to increased environmental productivity and stable shorelines in the Holocene. However, the pattern of population growth indicated by the archaeological record is not consistent with this. The rate of growth, although it appears dramatic on a millennial timescale, was extremely slow on an annual timescale. Over the last 5000 years, the average exponential rate of increase (r) in the radiocarbon record was 0.38 per thousand years, representing an annual growth of about 0.04 per cent per year. For comparison, during the last century, the global human population grew up to 50 times faster than this. The demographic response of an ancient human population to a stepped increase in carrying capacity would have been completed far more quickly than the long drawn-out process that is observed in the rockshelter record. If the growth that we observe was due to increased productivity, the process must have consisted of many small demographic adjustments in response to a long series of incremental increases in productivity that unfolded gradually over the whole of the Holocene. But the palaeo-environmental record of Australia does not reveal such a pattern of steady productivity increase. Temperature and rainfall increased rapidly during the latest Pleistocene, reaching values close to those of the present by 10 000 years ago. They then remained relatively stable for most of the Holocene, except for two major variations: (i) a period of slightly higher temperature and significantly higher rainfall than now from about 8000 to 5000 years ago [35]; and (ii) amplified climate variability owing to increased frequency of El Niño/Southern Oscillation (ENSO) events from the Mid-Holocene [36]. The first of these intervals should have seen elevated environmental productivity, but since then the human population of Australia ought to have been stressed by declining rainfall and buffeted by climatic extremes caused by ENSO fluctuations. Yet, population growth was higher during the last 5000 years than during the Mid or Early Holocene.

If the population of Australia did grow during the Holocene as indicated by the rockshelter record, this was probably owing to an extended series of changes in behaviour that enhanced the capacity of people to extract resources from their environment. This is, essentially, the explanation for population growth that is offered by Lourandos' intensification model [14]. But what triggered this process, and what accelerated it 5000 years ago?

Some archaeologists have argued that the onset of ENSO activity in the Holocene increased the risks of resource failure for Australian hunter–gatherers, who responded with technological and behavioural changes to minimize that risk [33] or made more use of fire to manage the landscape [21]. These changes may also have provided the capacity for population growth [11], which created new potential for cultural and technological changes, leading to further population growth, and so on [14]. Intensified use of seed resources could have been a key element of this cascading process [11,37]. Another possibility is that the arrival of the dingo *Canis lupus* and its adoption as a semi-domestic species was a catalyst for fundamental cultural transformation that initiated a series of changes like those envisaged in the ENSO hypothesis [38,39]. It is also possible that the demographic changes registered in the rockshelter record were at least partly owing to adaptive evolution, which may have been promoted by increased genetic variation supplied as a result of initial increases in population size [40]. However, the coincidence of accelerated population growth around 5000 years ago with either the onset of climate variability due to ENSO or arrival of the dingo is tenuous at best. The frequency of El Niño events began rising about 7000 years ago, and this rise continued, irregularly, to a peak about 1200 years [36]. Fossil evidence suggests that the dingo arrived in Australia about 3500 years ago, although this evidence cannot rule out a somewhat earlier presence [22].

Whatever the trigger, our results provide new support for the view, advocated by some Australian archaeologists [14] but contested by others [33], that something important happened to the human population of Australia during the Holocene, and that the Mid-Holocene in particular was a turning point in Australian prehistory. That this occurred independently of the re-organizations of human behaviour associated with the adoption and the spread of agriculture in other parts of the world points to the fundamental dynamism of human populations during the Holocene. The large increases in population density indicated by the rockshelter record, together with the fact that these increases seem to have been unconnected with environmental productivity, suggest that in Australia the environmental impact of hunter–gatherer people must have risen substantially through the Holocene.

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