Large size of the Australian Indigenous population prior to its massive decline following European invasion

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Abstract

Estimating the size of Indigenous populations in Australia prior to European colonial invasion is essential to truth-telling and reconciliation. Robust estimates of the population dynamics of pre-colonial Indigenous Australians are poor due to lethal diseases, frontier violence, and no systematic censuses. We review ethnographic observations, archaeological and genetic reconstructions, and modelled carrying capacity, to infer Indigenous population size prior to colonial invasion. This allows an estimate of the number of excess deaths in post-colonial times. Congruency of the modelled (not historical accounts) estimates suggests a bootstrapped pre-colonial median of 2.51 million, or 0.33 people km^{-2}. For a median pre-colonial population of 2.51 million, ~ 32,500 excess deaths $year^{-1}$ (2.39 million deaths in total) would have had to occur over the late 18th and early 19th Centuries from colonial invasion-related mortality. These findings highlight the major impacts of invasion experienced by Indigenous Australians, and demonstrate their survival, resilience, and recovery over the past 235 years.

Introduction

Determining the size of pre-colonial Indigenous populations in Australia and the trajectory of demographic change since the start of European invasion in 1788 is important in current attempts to achieve reconciliation between Indigenous Australia and the broader Australian community. Recent studies with a focus on truth-telling are beginning to show that impacts of colonial invasion were more substantial than previously recognised[1–3]. Quantifying the magnitude of the change since European invasion is essential for assessing and beginning to address the intergenerational trauma experienced by Indigenous communities today. It is also necessary to inform the suitability of modern socio-economic policies, and the nature of support provided by Commonwealth and State governments to Indigenous communities. 'Closing the Gap' — an important policy framework for improving the lives of Indigenous Australians — was established in 2008 and includes targets around cultural well-being derived from late 20th Century and contemporary data[4]. However, this policy would benefit from a longer record of demographic change.

Understanding the size and trajectory of Indigenous Australians populations can also inform archaeological, genomic, and palaeo-environmental studies — whether the continent was occupied by only a few thousand or several million Indigenous people will fundamentally alter how such records are interpreted. There is a growing debate about whether Australia's Indigenous people were well-attuned land and sea managers who had minimal impacts on flora and fauna, or whether they were active agents of large-scale environmental change, resource enhancement, and niche construction[5–10]. Quantifying the scale of the impacts is required to appreciate the extent to which Indigenous land management and transmission of Indigenous knowledge were impacted by invasion. Demography is an essential component of this debate, and a deeper understanding of population dynamics is required to inform ongoing and future landscape-management strategies based on traditional practices. For example, the application of Indigenous environmental management is becoming more commonplace (e.g., cultural burning)[11,12], and estimating the scale of such activities prior to 1788, in part driven by population size and distribution, would benefit in informing the application of these practices today[13].

The fundamental challenge to determining population size prior to invasion is accounting for the initial impacts of disease and frontier violence, which resulted in largely undocumented demographic effects throughout the late 18th and early/mid-19th Centuries[14–17]. Notably, smallpox — a highly virulent and deadly disease caused by variola virus — was observed within 15 months of the First Fleet reaching Sydney Cove on Gadigal country (Fig. 1), and contemporary observations suggest it had a massive negative impact on the population[16,18]. The spread and impact of this initial epidemic remains poorly quantified, but subsequent outbreaks throughout the 19th Century resulted in much of the remaining susceptible Indigenous population being exposed to the virus. Concurrently, an increasing colonial population established and expanded agriculture and pastoralism along the eastern and southern margins of Australia, resulting in widespread frontier violence. Focussed on the first half of the 19th Century, but extending to the 1930s, killing of Indigenous people was prevalent and rarely punished, with some accounts suggesting it was nothing less than a campaign of extermination[19]. While estimates of the number of people killed were rarely accurate in the historical accounts, and increasingly omitted entirely after 1838 as a result of successful prosecution of perpetrators of the Myall Creek massacre[19] (Fig. 1), several recent studies have suggested that the numbers killed were at least in the tens of thousands and potentially > 100,000[1–3,20]. It was not until the early 20th Century that anthropologists began to focus on the question of Indigenous population size, and not until 1971 was there a comprehensive census of Indigenous people (abs.gov.au/census).

Here, we present a review of estimates of the size of the pre-colonial Indigenous population derived using a range of approaches. We provide an analysis of congruence of estimates not derived from biased historical accounts, and then apply a demographic model to estimate the number of excess deaths implied by subsequent population decline. Our aim is to explore the congruence of past estimates to identify a baseline that can shed light on the demographics of the Indigenous population prior to colonial impacts, and subsequently over the past 230 years of occupation; and that can assist in future truth-telling, and socio-economic and environmental planning.

Previous population estimates using the historical record

Observations of Indigenous people, including their population size and composition, began from the moment of first encounter and expanded with the onset of colonial invasion. Colonial diaries often refer to encounters with small bands of people and infrequent references to major gatherings of several hundred individuals[21–25]. Indeed, Arthur Phillip, the first Governor of New South Wales, referred to some 1500 people living within a 16-km (10-mile) radius of Sydney Cove[24] (Fig. 1). Such examples of unsubstantiated population estimates were made across Australia throughout the 19th Century[26–28], but there was no systematic census of Indigenous people during that period. Accounting associated with the distribution of blankets to Indigenous people, introduced by Governor Lachlan Macquarie in 1814 and continuing into the early 20th Century, provides perhaps some of the earliest quantitative data from which to estimate population size. However, while this is an important source of family information, these data are not robust, and tracked only those who were present at distribution locales when blankets were distributed on a particular day each year. Such estimates are therefore unlikely to encompass the full cross-section of Indigenous populations in each region.

Radcliffe-Brown[31] compiled observations from a range of informants across Australia to provide the first continental-scale assessment of the Indigenous population. Applying these estimates, as well as some derived using basic assessments of environmental carrying capacity, he proposed a total population of between 250,000 and 300,000 people, equivalent to ~ 1 person 30.8 km^{-2} (i.e., 0.032 km^{-2}). While this range is widely cited, most reported observations are derived from data collected late in the 19th Century when populations had already been subjected to the impacts of colonialism. Radcliffe-Brown[31] was aware of this bias, and suggested that his estimates were almost certainly low, despite many researchers repeating his estimate as the probable total, or even maximum, pre-colonial population size.

Between the 1950s and 1970s, many researchers built on those previous estimates. Research during this time focussed either on (*i*) observed or recorded population densities and the extrapolation of these observations to regional or continental scales[32–34], or (*ii*) using the number of documented tribal groups across Australia, and the average number of people within each group, to calculate a total population for the country[33,35]. These analyses continued to suggest a pre-colonial Indigenous population in the range of ~ 200,000–350,000 people. Based on different sources, Smith[36] proposed 314,500 as part of a comprehensive review of census data throughout the last 200 years, although he also acknowledged that this was an underestimate. Smith[36] provided the most robust post-invasion estimates available through a combination of records, suggesting around ~ 200,000 at 1850, and dropping to their nadir of ~ 80,000 by 1930. Modern census data since 1971 show an upward trend in population size from 1930, with modern Indigenous Australians now numbering ~ 813,000 as of 2021 (abs.gov.au/census).

Butlin[14] was the first to highlight systematically the potential impact of disease on Indigenous populations and that this phenomenon might have affected early colonial observations. He suggested that previous estimates were too low because of disease and applied early computer simulations to account for this, suggesting a pre-colonial population of 900,000. By 1986, Butlin[37,38] increased his estimate to 1.1 million (range: 0.88–1.32 million). Butlin's[14] population estimate was largely supported by White and Mulvaney[39], but slightly decreased to 750,000 to account for uncertainties in colonial impacts in the tropics. Later, Mulvaney and Kamminga[40] revised this number to between 750,000 and 800,000. While population change has been a consistent focus for archaeological research since the 1980s, specific quantitative values have not been explored using documented sources.

Results

We summarise three independent approaches recently used to estimate the size of the pre-colonial Indigenous population in Australia that do not rely on historical observations. We describe a bootstrapping approach to determine the congruence range of the estimates, comparing quantitative modelled outputs to historical population density estimates. We then construct a demographic model estimating the number of excess deaths necessary to achieve the population declines inferred from pre-colonial estimates and late 19th Century observations.

Archaeological radiocarbon data

By applying the variation in average annual growth rate (‘Gr_{Ann}’) to an incrementing ‘initial’ founding population at 50 ka, and a compound interest equation, Williams[41] concluded that 1,000–2,000 people arriving 50,000 years ago would result in a population size of 1.2 million just prior to colonial invasion (ranging between 364,000 and 2.99 million depending on the size of the founding population applied and the degree of smoothing of the Gr_{Ann} across the 50,000-year record).

While progressing the debate from the historical and ethnographic records, there are several limitations with the Williams[41] approach. Notably, there are few radiocarbon data prior to ~ 46,000 years ago, and this constrains the ability to model the initial peopling event robustly, which is widely documented to have occurred at least 10,000 years earlier[42,43]. Williams[41] applied corrections for taphonomy — the loss of older archaeological deposits — to the dataset to compensate, but this approach also has limited validity prior to 25,000 years ago[44]. In the context of studies outlined in subsequent sections, Williams’ values[41] might similarly underestimate pre-colonial population size because some of the earliest phases of peopling and exploration across the continent were not considered. Despite this underestimation, colonial impact on Indigenous populations was included; however, limited data made valid conclusions difficult to verify.

Genetic estimates of effective population size

Tobler et al.[45] used mitochondrial DNA (mtDNA) from 98 Australian-only lineages to estimate an effective maternal population size (N_e^f) of ~ 154,000 to 1.2 million by the time of colonial invasion (Tobler et al.[45]; their Extended Data Fig. 7). Assuming an equal adult sex ratio, this predicts a total effective population (N_e) of 308,000 to 2.4 million. The ratio of census to effective population size, N_c:N_e, is > > 1[46], which is evidence in favour of a total population of at least several million based on genetic evidence alone. Malaspinas et al.[47] (their Figure S12.2) also used mtDNA as well as Y chromosome data to estimate N_e (N_e^f and N_e^m, for females and males, respectively), giving N_e^f = 11,480–421,314 (all mitochondrial genomes) and N_e^m = 205,016–2,935,490. Assuming an equal sex ratio, this places the total N_e range at 22,960–5,870,980.

Continental carrying capacity derived from net primary production

Based on the carrying-capacity estimated from net primary production[42,48], the estimated mean number of people in the entirety of Australia could have been as high as 5.22 million, or an average, Australia-wide population density of 0.68 km^{-2}. This number depends on the underlying relationship between human density and net primary production; assuming the best-supported non-linear rotated parabolic relationship demonstrates that the highest human densities would have occurred in the northern savannah region of Australia, the eastern and south-eastern coastal regions, and Tasmania[42].

Congruence of estimates of pre-Invasion population size

Including the 4 modelled estimates (carrying capacity[42,48], radiocarbon[41,49], $2\times N_e$[45,47]) into the bootstrap procedure provides a median of 2.51 million (75% confidence interval: 1.13–4.41 million), or 0.33 people km^{-2} (0.15–0.57 km^{-2}). Removing the Malaspinas et al.[47] estimate from the bootstrap procedure because of its higher uncertainty (0.023–4.87 million) provides a median of 2.34 million (75% confidence interval: 1.11–4.28 million), or 0.30 people km^{-2} (0.14–0.56 km^{-2}) (Fig. 2). These estimates of population density are not without precedent when compared to post-colonial estimates of hunter-gatherer densities in the temperate coastal regions of Australia (mean ± SD: 0.34 ± 0.24 people km^{-2}, and an upper estimate of 0.81 km^{-2}), further afield for Neolithic/Palaeolithic peoples of the Levant and Near East (0.13–1.32 km^{-2})[50], or for New Guinean transient agriculturalists (4.37 ± 4.22 km^{-2})[42,51]

Testing bias hypotheses for historical data

A linear plot of our density estimates *versus* those from the Binford[29] database supports our first hypothesis that relative densities are similar between the two sources (Fig. 3). Our estimates are consistently higher than those of Binford; however, this is expected because Binford's data[29] reflect a population already affected by colonial invasion and our methods are aimed at estimating a pre-colonial population size.

The final boosted regression tree (39,550 total trees) testing the remaining two hypotheses regarding expected bias explained 65.4 ± 8.0% of the variation in the ratio of the two densities (carrying capacity-derived *versus* Binford[29]) (relative influence: year = 57.5%, latitude = 42.5%). We found support for the second hypothesis that the deviation between the Binford[29] and carrying capacity-estimated density estimates increased through time (Fig. S4b). In partial agreement with the third hypothesis that the deviation between the two density estimates is lower in the tropical latitudes of Australia given the predominantly southern focus of the initial impacts of invasion, the ratio between densities was lowest in the highest latitudes (< 20° S), increased between ~ 20° S and 30° S latitude (from just south of Townsville to Coffs Harbour on the east coast, and just north of Port Hedland to Leeman on the west coast; Fig. 1), and then declined in the most southerly latitudes (Fig. 4a).

The overall results demonstrate that although the carrying capacity-estimated densities in our model are higher than those in the Binford[29] database, the broad geographic patterns are similar. Much of the disparity between the two estimates can be explained by geography (relative remoteness from primary European settlements) and the time since initial colonial invasion. This result confirms our hypotheses regarding spatial and temporal biases in historical estimates. An additional spatial comparison between modelled population sizes and historical estimates from relatively undisturbed populations demonstrates strong support for a power-law relationship (Supplementary Information Appendix II), suggesting that the carrying-capacity estimates are the correct order of magnitude.

Estimate of excess deaths following colonial invasion

For a population at the bootstrapped mean pre-colonial estimate of 2.51 million to decline to 0.177–0.193 million by 1861 (73 years), an average of around 32,500 excess deaths year^{-1} must have occurred (Fig. 5a), with the rate itself likely varying through time. This means that in total, approximately 2.39 million excess deaths occurred over the 73 years from 1788 to 1861 (Fig. 5b). Results were similar when we projected to 1901 instead of 1861 (~ 24,100 excess deaths year^{-1} on average for a total of 2.72 million excess deaths; Supplementary Information Appendix III, Figure S4). This translates to an instantaneous exponential rate of annual decline = -0.036 (Fig. 5a). Of course, given the wide uncertainty in the pre-colonial estimates (75% confidence interval: 1.13–4.41 million), the total number of excess deaths could have ranged from ~ 0.75 million to 5.0 million (Fig. 5b).

Discussion

We have reappraised the Indigenous population size prior to European invasion, and demonstrated that it was far larger than previously proposed. Over the years, several different methods have been applied to determine the size of Indigenous populations in the past. Initially, these focussed on ethnographic and historical observations of early post-invasion tribes, family groups, and gatherings. Radcliffe-Brown[31] perhaps epitomised these approaches, and his downwardly biased estimate of ~ 300,000 has been used as the benchmark influencing all other studies for much of the mid- and late 20th Century. However, it has become increasingly apparent that disease had a large impact on these populations. For example, Dowling[16] suggested that the introduction of smallpox in 1789 might have resulted in a loss of 50% of the population, a percentage comparable with other contemporary observations of the impact of the disease[15]. Furthermore, there were subsequent smallpox outbreaks in 1826–1838 and 1860–1869, as well as other diseases such as measles[53], influenza[54], tuberculosis[55,56], leprosy[57], and syphilis[58]. Thus, earlier population estimates are based on observations of an already compromised population, and must be considered to reflect only a proportion of the pre-invasion population size.

Alternative approaches using archaeological, genetic, and carrying-capacity methods all suggest higher estimates than historically biassed approaches. Although Williams[41] was one of the first to explore methods that do not rely on historical observations, his estimates were among the most conservative at between 1.2 and 3 million. Limitations of the radiocarbon technique resulting from taphonomic biases, especially in the pre-Last Glacial Maximum period, suggest therefore that his estimates should be considered minima. Similarly, genetic data also suggest upper limits of effective population size from ~ 2.4 million[45] to ~ 5.9 million[47], acknowledging again that these likely do not represent the entire census population size.

Most recently, Bradshaw et al.[42] proposed a population of ~ 5 million people. Despite being more complex, this type of carrying capacity approach is similar to the methods applied by Campbell[32] and Radcliffe-Brown[31] — all of whom estimated densities of people by environment area. While the Bradshaw et al.[42] estimates are higher than those produced through other techniques, additional testing using early colonial observations of Aboriginal populations by Binford[29,59] (Supplementary Information Appendix III) show anticipated biases according to time since invasion, and those considered unaffected by initial diseases show the carrying capacity approach closely predicts these observations, and provides a robustness that is not easily achieved by other techniques.

When considering the various techniques applied, the balance of evidence supports a probable population of at least > 1 million, but more likely > 2–3 million, and potentially > 5 million at the time of invasion. Although our new estimates might appear high after nearly a century of low estimates cited in the literature, our median bootstrapped estimate still equates to 0.33 people km^{-2} (0.15–0.57 km^{-2}), well within observed population sizes in temperate and tropical Australia during the colonial period[51] — noting that those very observations would have already been subjected to colonial impacts. The median pre-colonial population size we estimate here also implies that the total human population in Australia reached its post-colonial (and perhaps also during the last 60,000 + years[42,48,60]) nadir around 1836 at ~ 570,000 (Supplementary Information Appendix IV, Fig. S5). Our reconstruction also suggests that the size of the non-Indigenous population first exceeded that of the Indigenous population around 1847 on average (Supplementary Information Appendix IV, Fig. S5).

Comparing our updated pre-invasion estimates with those made during the colonial period reveals the extent of the catastrophe that befell Indigenous populations. We estimate that a median of 2.4 million additional people might have died through disease directly or indirectly through broader social impacts, and/or were killed in frontier violence in the early and mid-19th Century. Even adopting the lowest pre-invasion estimates of total population size, our model predicts that there would have been ~ 750,000 excess Indigenous deaths between 1788 and 1861. This massive post-colonial depopulation event is also evident from genomic analyses of 159 individuals from four Indigenous communities (Tiwi, Titjikala, Galiwin'ku, and Yarrabah; Fig. 1) that suggest a decline of 1 to 2 orders of magnitude in effective population size over the last few hundred years[61] (their Fig. 5a). While disease is considered to have been the main driver of this loss, recent exploration of frontier violence using government archival records (e.g., Native Police) suggests it caused far more deaths than are documented in published histories of Australia, with recent estimates suggesting 100,000 people may have been killed in frontier violence[3]. Further, our results suggest that the number of disease-related deaths was comparable, and possibly much higher. When compared with 1861 census data, only about 7–8% of the median estimated population survived the initial invasion. Such changes would have been catastrophic to Indigenous people, their traditional customs, and life ways. However, Indigenous people adapted remarkably to their changing landscapes and social structures, modifying and continuing to pass on essential Dreaming, kinship, lore, and other traditional knowledges, as well as keeping language alive in various forms, to ensure retention by the broader Indigenous community. It is also unsurprising that such information might be fragmentary and/or incomplete across some parts of Australia where impacts were most extensive[62,63].

While there has been growth of the Indigenous population in the late 20th Century, contemporary Indigenous populations remain at only 32% of their median estimated pre-invasion size. Assuming average growth observed since 1971 remains constant, it might not be until 2050 that populations reach parity with the estimated median size in 1788. It is in this context that reconciliation, engagement, and future policy making must be prioritised with Indigenous people — people that were brought near the brink of extinction, who remain at a fraction of their pre-invasion abundance, and who continue to suffer intergenerational trauma from these historical events. Equally, the broader Australian community should embrace the rich culture that survived these events, and that remains an integral part of Australia's cultural fabric to this day.

Methods

Archaeological radiocarbon data

Williams[41] and Williams et al.[49] compiled a large dataset of 5044 radiocarbon dates recovered from archaeological research since the 1950s from across Australia. They used this database to explore both qualitative and quantitative population change through time. Williams' approach[41] was to assume that each radiocarbon date reflected evidence of the activities of a discrete population at a particular point in time. These combined data provided a continent-scale indication of populations, with more data reflecting more people and *vice versa*. Binning the data and calculating the rate of change between bins produced a semi-quantitative index of increase or decrease in population size through time, providing an average annual growth rate ('Gr_{Ann}').

Genetic estimates of effective population size

Various estimates of effective population size (N_e) for the pre-colonial Indigenous population have been calculated using mitochondrial (mtDNA) and Y-chromosome DNA (Y-DNA)[45,47]. However, census population size (N_c; i.e., number of individuals censused in a population) rarely equals N_e because of deviation from random breeding[46]. In fact, multispecies assessments estimate an average N_e:N_c ratio ~ 0.10[46], and while the true ratio is unknown for Indigenous Australians prior to colonialism, N_e:N_c is almost certainly < < 1. Nonetheless, we took the range of N_e derived from mtDNA from Tobler et al.[45] (their Extended Data Fig. 7) and doubled it (assuming an equal sex ratio) to infer total N_e (i.e., because mtDNA-based analyses of N_e estimate the female component of the population[64]). Likewise, we took the N_e range of all mitochondrial genomes and all Y chromosomes from Malaspinas et al.[47] (their Fig. S12.2C,D), added them, and took the resultant full range to infer total N_e.

Continental carrying capacity derived from net primary production

Bradshaw et al.[42] constructed a stochastic cellular-automaton model to predict the rate of settlement after the first people entered Sahul during the Late Pleistocene. The model was partially predicated on estimates of human carrying capacity (expressed in densities; people km^{-2})[65] derived from estimates of net primary production (kg C m^{-2} $year^{-1}$) hindcasted using the LOVECLIM Earth-systems model[66]. These relationships were established between net primary production and measured hunter-gather densities[65], so they already account for people's capacity to modify landscapes to improve resource yields. Later, Bradshaw et al.[48] combined the cellular-automaton model with estimates of likely movement corridors ("superhighways") from Crabtree et al.[67] to revise the projections for the rates of dispersal.

Using the combined model, we extended the projections to the present in this study, but instead used estimates of net primary production derived from the more recent HadCM3 global circulation model[30] to calculate human carrying capacities. HadCM3 is potentially more accurate than LOVECLIM in estimating vegetation trends during the Last Glacial Maximum in Sahul[68], so we determined it would provide better estimates of human carrying capacity for Australia immediately prior to European invasion.

Congruence of estimates of pre-Invasion population size

We developed a bootstrapping procedure to determine the central tendency of the carrying-capacity, radiocarbon, and genetic N_e model estimates for the pre-colonial population (N), thereby avoiding the downward biases inherent in estimates reliant on historical records. To do this, we first calculated the standard deviation of the radiocarbon and the two N_e estimates, then computed 10,000 Normally distributed deviates for each series using the *rnorm* function in R[69]. For the single carrying capacity-based estimate, we first computed the mean of the coefficient of variation from the other modelled ranges and used this to calculate a standard deviation for the carrying-capacity estimate. We then compiled 10,000 truncated Normal deviates of the latter (upper limit = single estimate = 5.22 million) using the *rtruncnorm* function in the truncnorm library[70] in R[69]. Finally, we combined the 10,000 deviates from each of the four models and calculated the median and upper/lower 75% confidence intervals.

Testing bias hypotheses for historical data

The carrying-capacity reconstructions of pre-colonial population size are the only spatially explicit model estimates, so we compared point estimates of these reconstructions to the same point-estimate densities from the Binford[29] hunter-gatherer database. Binford's[29] database includes > 200 variables incorporating various aspects of the mobility, social organisation, demography, and subsistence for 339 ethnographically documented groups of hunter-gatherers. Using the *LRB* function from the binford library[59] in R[69], we extracted population density, area of coverage, spatial coordinates (latitude/longitude), and corresponding year for the 49 entries in Australia. Next, we overlaid these point coordinates onto a 0.5° × 0.5° latitude/longitude grid of Australia with the cell-specific densities derived from the HadCM3 net primary production model (Fig. 1).

We first hypothesised a linear (but not necessarily 1:1) relationship between the Binford and the modelled density estimates if the carrying capacity model predicts a realistic density range across the area covered by the 49 point estimates from Binford[29]. However, the Binford[29] estimates span 1830–1978, and so encompass the entire period of demographic disruption brought about directly or indirectly by colonial invasion. Our second hypothesis is therefore that the deviation between the Binford[29] and modelled density estimates increased through time from 1788. We also hypothesise that the deviation between the two density estimates will be lower in the tropical (lower) latitudes of Australia given the predominantly southern focus of the initial impact of invasion. To test the last two hypotheses, we developed a boosted regression tree approach with the response coded as the ratio between model and Binford[29] densities, and the predictors of latitude and year, using the *gbm.step* function in the dismo library[71] in R[69] (error family = Gaussian, maximum number of trees = 100000, tolerance = 0.0002, learning rate = 0.00025).

Estimate of excess deaths following colonial invasion

To determine the number of excess deaths beyond those expected for an undisturbed population (i.e., those resulting from disease, massacres, and mortality associated with displacement and other colonial-related disturbances to Indigenous ways of life), we developed a stochastic population model using the age-structured matrix model developed for Indigenous hunter-gatherers by Bradshaw et al.[72]. We applied a density-feedback function that reduced survival evenly across all age classes to ensure average stability over the projection interval (see below) as developed by Bradshaw et al.[73]. Next, we resampled the survival and fertility vectors of the transition matrix assuming a standard deviation of 0.05μ (where μ = the mean age-specific survival or fertility estimate) based on a β and Normal deviate function, respectively.

From this model we obtained increasing values of annual 'excess' deaths (i.e., beyond those expected from the age-specific survival probabilities in the stable model) and subtracted this (separated by age class following the stable age structure derived from the deterministic matrix) from the updated abundance vector over a projection interval (73 years) from 1788 (colonial) to 1861 (Smith's[36] [his Fig. 8.6.3] reconstructed estimate of 0.177–0.193 million). Given the uncertainty of the Smith[36] estimate for 1861 (likely also underestimated), we also repeated the procedure for the projection interval from 1788 to 1901 (Smith's[36] [his Fig. 8.6.3] reconstructed estimate of 0.092–0.134 million).

For different 'initial' (i.e., pre-colonial) total population sizes ranging from 5.0 to 1.0 million inhabitants (in 0.5 million increments), we calculated the average annual and total number of excess deaths that would have been required to change the population from the initial abundance to 0.177–0.193 million by 1861, and to 0.092–0.134 million by 1901. We also expressed these outcomes in terms of the instantaneous exponential rate of decrease ($r = \log_e(N_{t+1}/N_t)$, where N_t = population size at time t) and the total excess deaths divided by initial population size (proportion of pre-colonial N).

Declarations

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Figures

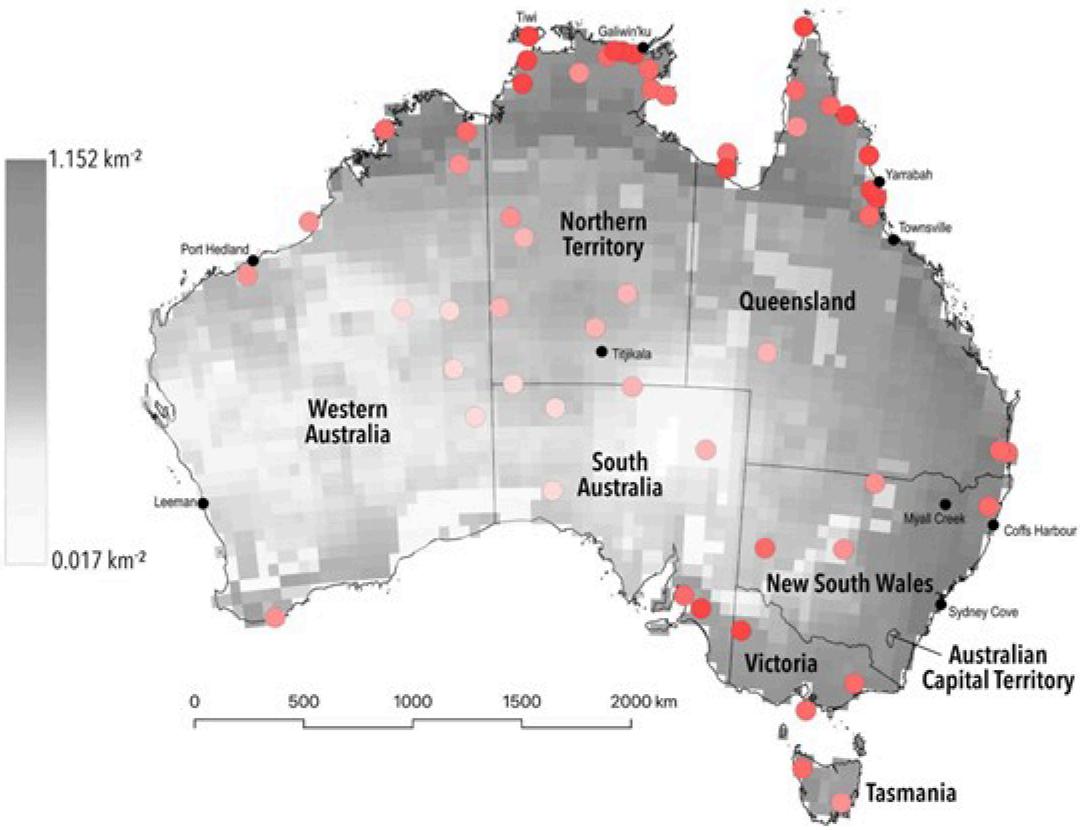

Figure 1

The 49 ethnographic entries from the Binford[29] hunter-gatherer database (red dots — darker red indicates relatively higher densities) overlaid on the HadCM3[30] net primary production-derived estimates of human carrying capacities (expressed in people km^{-2}). States and territories indicated. Legend indicates relative densities (greyscale). Also shown are several place names mentioned in the text.

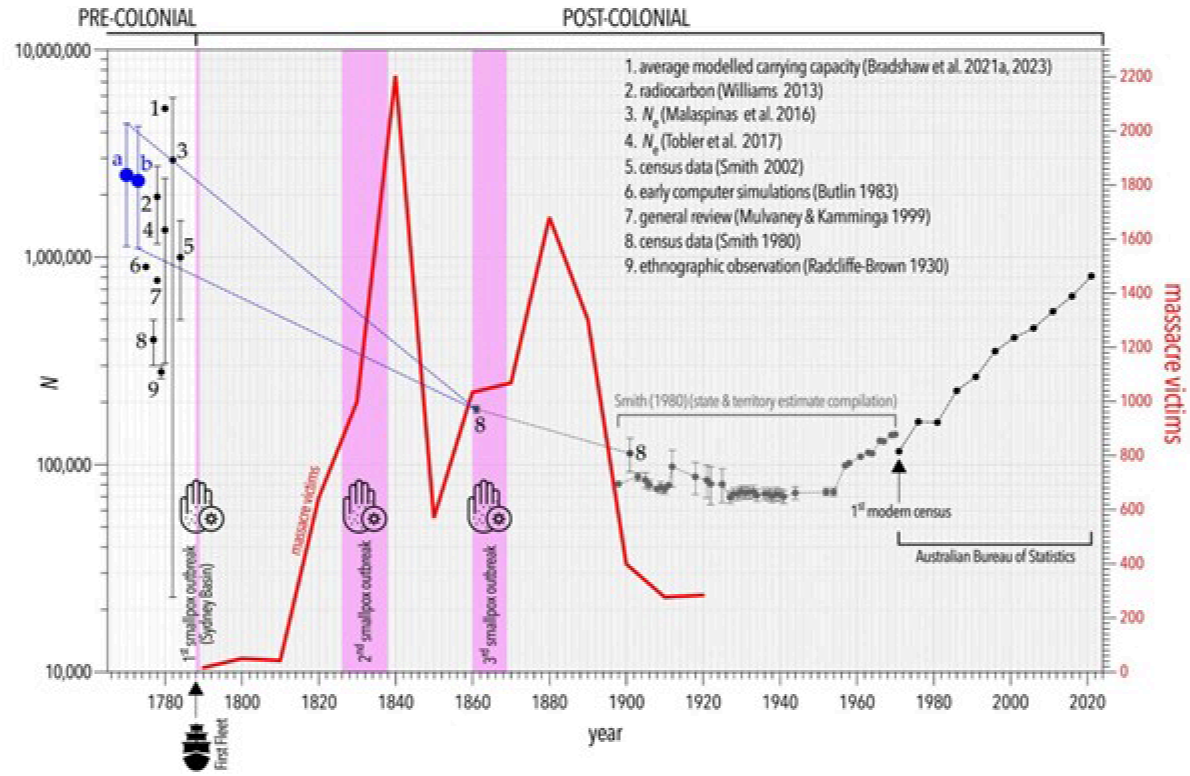

Figure 2

Timeline of putative population estimates of Indigenous (Aboriginal) Australians from just prior to colonial invasion in 1788 (jittered on *x* axis for clarity; *y* axis on $\log_{10}$ scale; see Supplementary Information Appendix I, Fig. S1 with linear-scale *y* axis) up to the last full census in 2021. Three major smallpox outbreaks are indicated in pink. Pre-colonial estimates include (1) average modelled carrying capacity (Bradshaw et al.[42,48]), (2) archaeological radiocarbon date reconstruction[41], genetic effective population sizes (N_e) from (3) Malaspinas et al.[47] and (4) Tobler et al.[45], and various historical estimates (5. Smith[52]; 6. Butlin[14]; 7. Mulvaney & Kamminga[40]; 8. Smith[36], 9. Radcliffe Brown[31]). Grey dots and ranges for 1861 and 1901 (indicated as '8') are derived from Smith[36] (his Fig. 8.6.3, p. 308). Grey dots from 1898–1970 and associated ranges are from the compilation of state and territory estimates by Smith[36], and black dots from 1971–2021 are census data from the Australian Bureau of Statistics (abs.gov.au/census). The blue dots and blue error bars indicate the bootstrapped 75% confidence interval for the (a) modelled estimates (i.e., carrying-capacity[42,48], radiocarbon[41], and N_e[45,47] models) and (b) without the Malaspinas et al.[47] N_e (given extremely wide confidence intervals). Also shown is the estimated total number of frontier massacre victims by decade from the 1790s to the 1920s (red line; right *y* axis) from the Colonial Frontier Massacres in Australia 1788–1930 database[1].

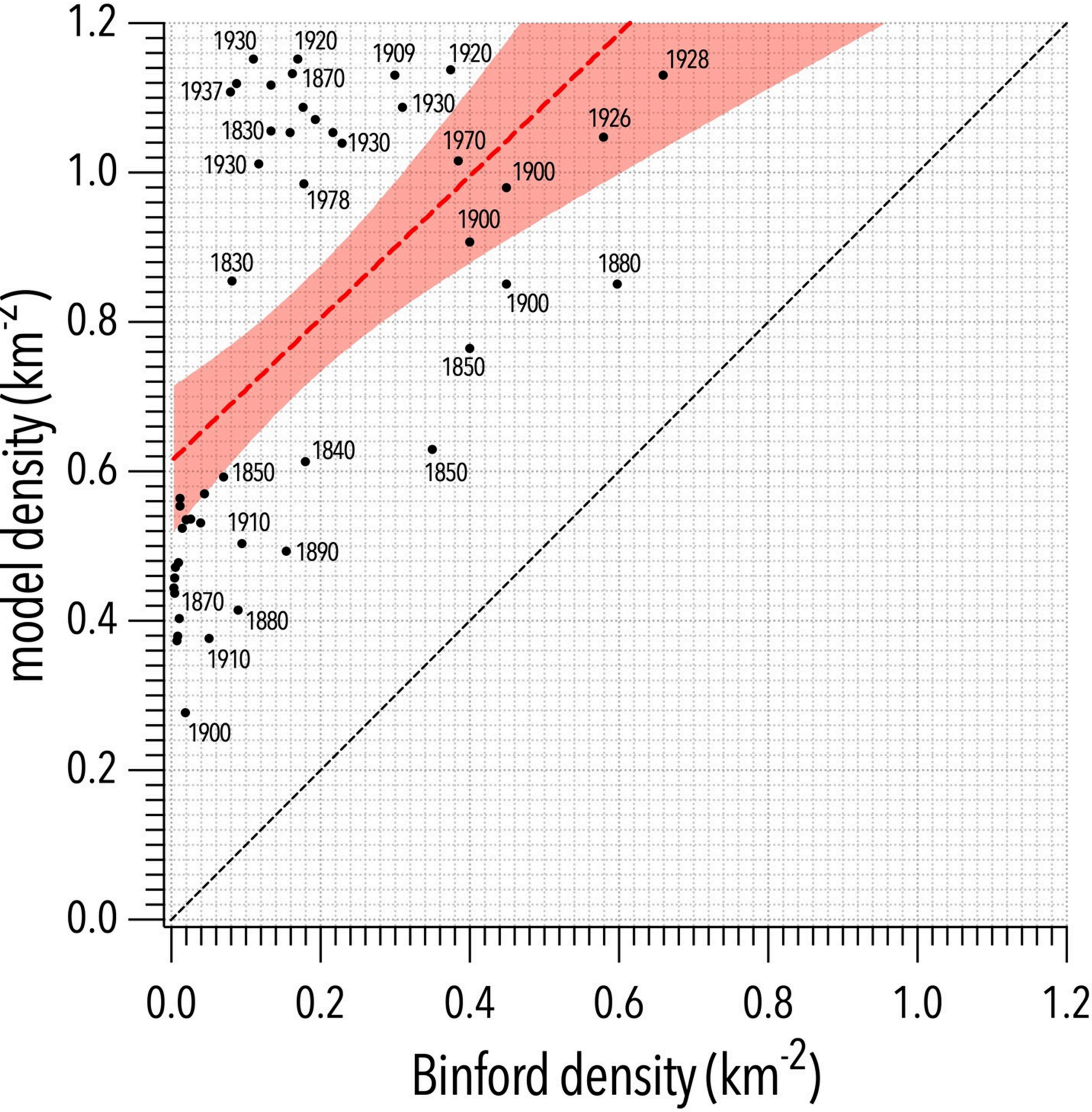

Figure 3

HadCM3[30] net primary production-derived estimates of human carrying capacity (expressed as a density: people km^{-2}) relative to 49 ethnographic entries from the Binford[29] hunter-gatherer database showing estimated densities (people km^{-2}). Dashed black line indicates the 1:1 relationship. Dashed red line and red shading show the linear regression and 95% confidence intervals of the predicted values (R^2 = 0.323; slope = 0.55–1.36; intercept = 0.52–0.71; model density = 0.9534×Binford density + 0.6139).

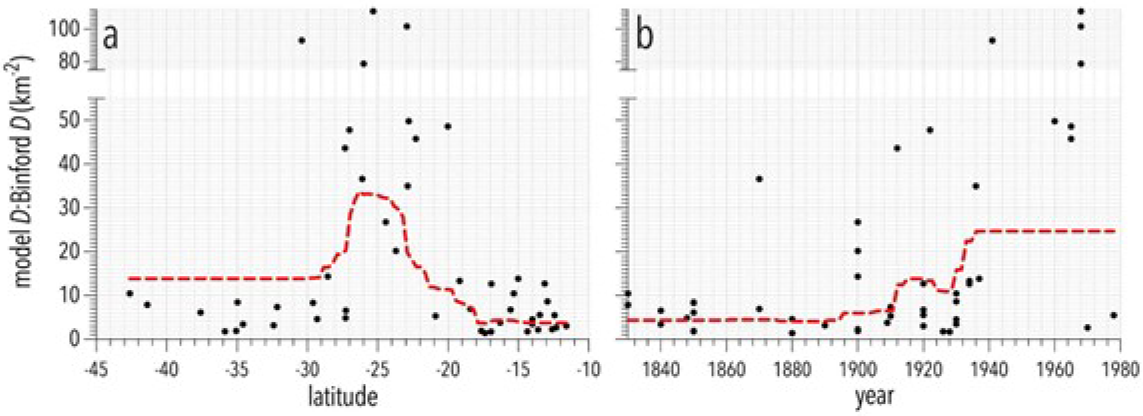

Figure 4

Ratio between the HadCM3[30] net primary production-estimated carrying capacity in terms of human density (*D*, people km^{-2}) and the densities derived from the Binford[29] ethnographic database against (a) latitude, and (b) year.

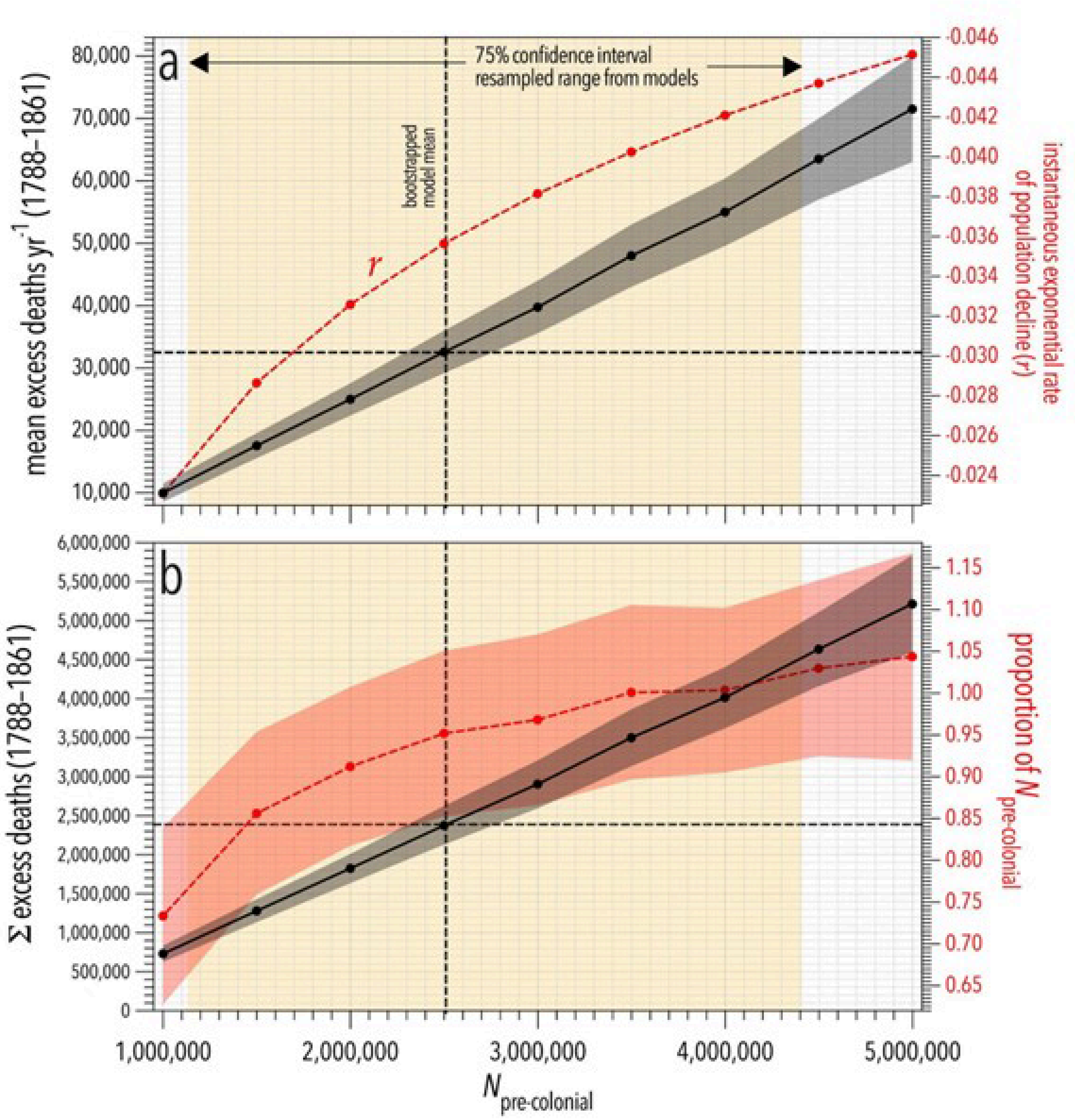

Figure 5

Excess deaths required to change a pre-colonial Indigenous population from sizes ranging between 5.0 million and 1.0 million to 0.178–0.193 million from 1788 to 1861 based on a stochastic demographic model. (a) For different initial population sizes (*x* axis), the left *y* axis shows the average annual excess deaths that must occur for the population to reach the indicated target, expressed as an average annual instantaneous exponential rate of population decline (*r*) on the right *y* axis. Grey shaded area indicates the 95% confidence intervals for the annual excess death estimate. Background peach colour indicates the 75% confidence interval of the resampled initial population sizes derived from the modelled sources (i.e., carrying-capacity[42,48], radiocarbon[41], and N_e[45,47] models; Fig. 1), and the black vertical dashed line indicates the central tendency of those estimates (bootstrapped model mean) and the black horizontal dashed indicates the annual excess deaths at that central tendency. (b) For different initial population sizes (*x* axis), the left *y* axis shows the sum of the excess deaths from 1788–1861 required to achieve a population of 0.092–0.134 million, expressed as a proportion of the initial population size on the right *y* axis. Grey and red shaded areas indicate the 95% confidence interval for each measure, and the vertical and horizontal black dashed lines are as in panel a.

Supplementary Files

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