



A critical review of radiocarbon dates clarifies the human settlement of Madagascar

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ABSTRACT

The timing of the human settlement of Madagascar, one of the last large landmasses to be settled by people, remains a key topic of debate in archaeology. Despite decades of research, recent estimates for initial settlement are increasingly divergent and span ca. 9000 years: the widest colonization window for any island within the reliable range of radiocarbon (^{14}C) dating. ^{14}C dating of archaeological sites and remains of butchered animals provide important evidence of when the island was first settled, but the reliability of these dates requires critical evaluation. Applying principles of chronometric hygiene, we present the first systematic review of Madagascar's ^{14}C chronology to clarify the island's settlement. Our findings support human presence by *at least* 2000 cal BP and suggest that an Early Holocene arrival is possible. The nature of such an early presence on the island, however, remains elusive due to a lack of contextual information.

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1. Introduction

Madagascar, the fourth largest island in the world, is situated roughly 250 miles off the East African coast. Despite its proximity to the cradle of humankind, the island was long thought to have remained uninhabited by people until the Late Holocene (Dewar and Richard, 2012). For decades, estimates of first human arrivals on Madagascar had ranged from 1500 to 2000 calibrated years before present (cal BP, Burney et al., 2004; MacPhee and Burney,

1991), suggesting the island was one of the last large landmasses on earth to be settled by people. Recent archaeological excavations and dating of butchered animal bone, however, have revealed evidence of a much earlier (Middle and Early Holocene) human presence (Dewar et al., 2013; Hansford et al., 2018). Meanwhile, recent dismissal of other evidence for human processing of animals (e.g. cutmarks on animal bone) has led to relatively conservative estimates of first human arrivals (Anderson et al., 2018b; Mitchell, 2019). Archaeological data from many regions of the island remain limited, and the reliability of existing radiocarbon (^{14}C) dates obtained from archaeological materials has never been comprehensively evaluated. Recent estimates of first human arrival on Madagascar thus diverge by ca. 9000 years, the widest colonization window of any island within the reliable range of ^{14}C dating,

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highlighting the need for a critical and systematic review of all known ^{14}C dates derived from archaeological materials on the island. Here, we present a compilation of published and previously unpublished ^{14}C data, along with associated data quality. This compilation should provide a useful resource to guide future research and inform ongoing discussions regarding past human activity on Madagascar.

In other regions of the world, the application of chronometric hygiene to evaluate the reliability of ^{14}C chronologies has improved our understanding of the timing and process of human settlement of islands (Spriggs, 1989; Wilmshurst et al., 2011), human dispersal on continental landmasses (Graf, 2009; Pettitt et al., 2003), and megafaunal extinction (Barnosky and Lindsey, 2010; Meltzer and Mead, 1985; Stuart and Lister, 2012). In some cases, systematic evaluation of ^{14}C dates has significantly constrained date ranges for initial arrival and subsequent settlement progression (Fitzpatrick, 2006; Wilmshurst et al., 2011). Here, we present the results of the first systematic review of existing ^{14}C dates for archaeological sites and materials on Madagascar, in order to clarify the timing of initial human arrival. Much of the urgency of resolving Madagascar's settlement chronology rests on the rate and manner in which human settlers altered the island's landscapes and ecologies. For example, the population crash of a suite of endemic animals (all taxa >10 kg) occurred relatively rapidly around 1000 years BP (Crowley, 2010). Depending on the precise timing of initial human arrival and the subsequent progression of human settlement and activity across the island, the population crashes leading to these extinctions may have been rapid or protracted. If people did arrive on Madagascar in the Early Holocene, human communities co-existed with now-extinct fauna for millennia, making the island's extinction trajectories more comparable to examples of protracted extinctions (e.g., Jones et al., 2008) than to rapid human-driven extinctions (e.g., Steadman, 2006). The case for an extended coexistence between human and megafauna populations has recently been challenged on two grounds: 1) previously recorded cutmarks on megafauna remains are the result of non-anthropogenic taphonomic processes, and 2) dates derived from these remains do not provide reliable estimates of human presence (Anderson et al., 2018b). This paper addresses the second issue, focusing on ^{14}C dates.

Beyond ^{14}C -dated bones bearing cutmarks, there is little contextual information from archaeological sites about early human presence on Madagascar. The challenge of identifying an early human presence is significantly complicated by the fact that different social, political and economic configurations (e.g. hunting and foraging versus pastoralism and farming) leave different traces in the material record that range from conspicuous to practically imperceptible. Only one mid-Holocene archaeological site has thus far been identified – the Lakaton'i Anja rock shelter in the far north (Dewar et al., 2013). Given the ephemeral nature of early sites, the possibility that an initial arrival estimate represents the time of a shift in type of human activity cannot be excluded (Dewar et al., 2013; Douglass and Zinke, 2015; Ekblom et al., 2016; Godfrey et al., 2019).

2. Materials and methods

2.1. Dataset

We evaluate a compiled list of ^{14}C dates ($n=199$) that are associated with traces of past human activity from sites across Madagascar ($n=64$; Fig. 1). This compilation includes published ^{14}C dates from the literature ($n=170$) and ^{14}C laboratory records ($n=5$; Dataset S1), as well as previously unpublished dates provided by the authors ($n=24$, see S2).

In order to compile the database, we comprehensively reviewed the published archaeological literature on Madagascar. We also contacted all ^{14}C laboratories known to have analyzed published Malagasy material (Table S1), in order to compile previously unpublished dates in ^{14}C laboratory databases. It is possible that some unpublished dates exist in laboratory records that are unknown to us. Of the laboratories known to have analyzed published Malagasy material, some are closed, some did not reply to our inquiry, and some were unable or unwilling to check their records for unpublished data from Madagascar (Table S1). A small number of Optically-Stimulated Luminescence (OSL) dates are also available for archaeological sites on Madagascar. A review of OSL dates, however, was considered beyond the scope of this review, as OSL dating involves a set of reliability criteria that would have been difficult to integrate with our approach to reviewing ^{14}C dates. For full contextual details relating to previously published dates, we compiled a reference list of the publications in which these dates first appeared (Dataset S1). To effectively evaluate these data, we have worked to overcome the oft-noted challenge of interpreting partially-reported data quality information in the published literature (Graf, 2009; Wood, 2015). We include all available data associated with each compiled date in our database, including pretreatment, collagen yield, atomic C:N and stable isotope data, and we indicate missing data when necessary (Dataset S1).

2.2. Date ranking

Following the approach of Wilmshurst et al., we first categorized all dates according to material type (e.g. short-lived plant remains, eggshell, or purified terrestrial animal bone collagen) and evidence type (artifact/feature, butchery, or introduced species) (Wilmshurst et al., 2011). We then ranked the dates according to the quality of the ^{14}C data, based on interpretation of both context and laboratory method (e.g., Graf, 2009; Pettitt et al., 2003). Specifically, we based our ^{14}C hygiene procedure on 1) the reliability that the calibrated age of the material submitted for analysis matches the time of the target event (i.e. human activity), 2) the precision of the measurement, and 3) our confidence in the association between the dated material and past human activity (Fig. 1). This created a total of four overall rank classes (Figs. 2–3). In the paragraphs that follow, we outline our rationale for each criterion and how we sum ranks across criteria to assign each ^{14}C date to one of the four overall rank classes (Fig. 2).

2.2.1. Rank by material type

Based on material type, we assign each of the 199 dates in our database to one of two reliability classes. Reliability rank 1 dates include identified short-lived plant remains, purified terrestrial bone collagen, and bird eggshell. These materials have few problems associated with inbuilt age and contamination and are thus considered to be most reliable for recognizing the time of past human activity. Reliability rank 2 dates include identified long-lived plant remains, unidentified plant remains, unpurified residue of terrestrial animal bone, and marine and estuarine shell. Rank 2 dates are less reliably associated with the time of the target event for the following reasons: a) unidentified and long-lived plant remains may have significant inbuilt age due to the difference between the time of plant tissue death and human modification of the tissue (Dye, 2000; McFadgen et al., 1994), b) bulk terrestrial animal bone may include significant post depositional contamination (Higham et al., 2006), and c) imprecise corrections for marine and freshwater ^{14}C reservoirs complicate the interpretation of dates from marine and terrestrial shell respectively (Petchey et al., 2008; Reimer and Reimer, 2001; Rick et al., 2005). Avian eggshell carbonate has the potential for inbuilt age due to a

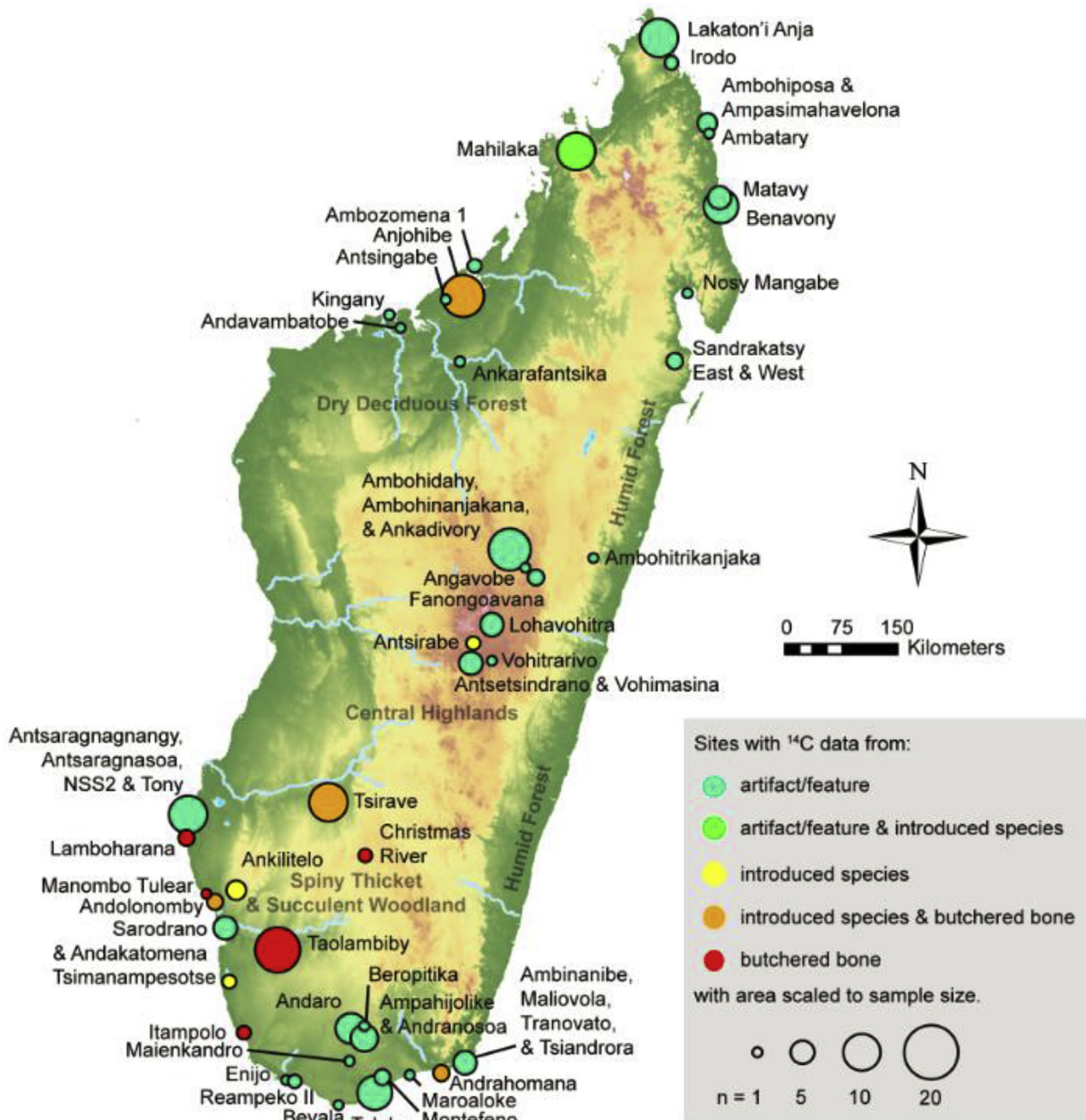


Fig. 1. Sites on Madagascar with ^{14}C -dated traces of past human presence. Circle colors denote ^{14}C sample type, and circle areas are scaled to ^{14}C data sample size. Note that Taolambiby ($n = 18$) is the site with the largest sample size and that numerous sites include just one piece of ^{14}C dated material. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

hen's possible intake of fossil lime during the laying period (Vogel et al., 2001), but we include avian eggshell as a reliability rank 1 material due to the fact that experimental studies do not consistently observe an effect of fossil lime consumption on the ^{14}C content of eggshell carbonate (Long et al., 1983).

Though we consider avian eggshell to be a stable biomineral and reliable material for radiocarbon dating (Higham, 1994), we exclude nine ^{14}C dated elephant bird eggshell fragments from the site of Talaky (southern Madagascar). The Talaky eggshell, which is hundreds to thousands of years older than eight associated and ^{14}C dated charcoal fragments in the midden (Ramsey et al., 2002), appears to be intrusive and is most likely not associated with human activity at the site. Given that the Talaky dune system is a high energy depositional environment and that the original excavators

report mixing of the deposits (Battistini et al., 1963), there is a strong possibility that the Talaky eggshell predates human activity. Additional research should investigate the possibilities that 1) these eggshell fragments were modified in the past by people and 2) these eggshell fragments come from eggs that may have been harvested by people. Given that the current data from Talaky suggest that human activity is associated with the deposition of charcoal and not the breakdown of the elephant bird egg fragments, we omitted these eggshell dates from our review.

2.2.2. Rank by precision

When a conventional ^{14}C age (CRA) is imprecise (often due to limited sample size), calibrated age ranges may span a large period of time and be unhelpful in clarifying the timing of past events, so

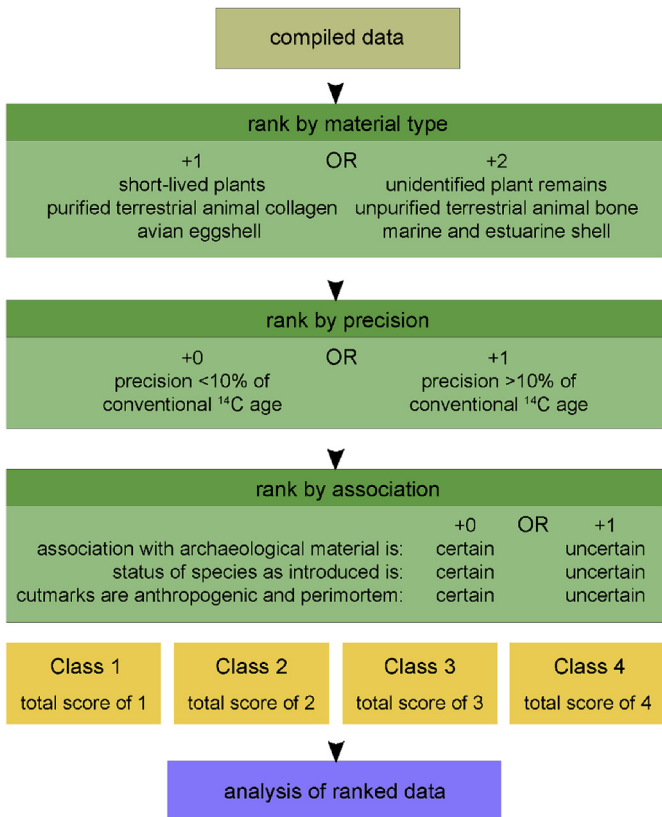


Fig. 2. Flowchart outlining the system of ranking the reliability of ¹⁴C dates. Dates are ranked as Class 1, 2, 3 or 4 dates, based on their material type, precision and association with human activity.

several researchers have chosen to consider precision in their assessments of ¹⁴C data quality (e.g., Graf, 2009; Wilmshurst et al., 2011) or to avoid considering relatively imprecise ¹⁴C data

collected before the widespread use of accelerator mass spectrometry (AMS, e.g., Stuart and Lister, 2012). Following Wilmshurst et al. (2011), we accounted for measurement error in our classification by adding “1” to reliability rank 1 and 2 dates if the measurement error was >10% of the CRA. We acknowledge that imprecise dates are not necessarily inaccurate and that significant inaccuracy in inferred dates for events follows from poor choice of dated material and poor association between the dated material and event of interest. However, it is worth noting that our precision criterion ultimately does not exclude critical dates from our highest quality class (Class 1), because all but two imprecise dates are either from poorly ranked materials or are poorly ranked due to questionable association with past human activity. The two exceptions (CAMS 142875 and CAMS 142892) are from the purified collagen of two dogs that likely died during the 19th century and are thus of relatively little importance in discussions of early human activity on Madagascar.

2.2.3. Rank by association

Dated material associated with past human activity includes introduced plant or animal remains, cutmarked bone, and any material found with archaeological artifacts or features. Whenever the status of a human-introduced species is questionable, the antiquity of cutmarks on bone is uncertain, or the integrity of an archaeological site is compromised, we added “1” to reliability/precision rank 1, 2, and 3 dates. We thus conclude with a total of 4 overall date rank classes. **Class 1 dates are those that are most reliable, precise, and clearly associated with human activity.**

2.3. Calibration

We calibrated ¹⁴C dates in OxCal 4.3 using the Southern Hemisphere calibration curve SHCal13 (Hogg et al., 2013). For the three marine samples in our database (two worked *Turbo* gastropod shells, both from Velondriake in SW Madagascar, and one gastropod shell from Irodo in northern Madagascar), we applied a conservative ΔR marine correction of 200 ± 50 years (Southon et al.,

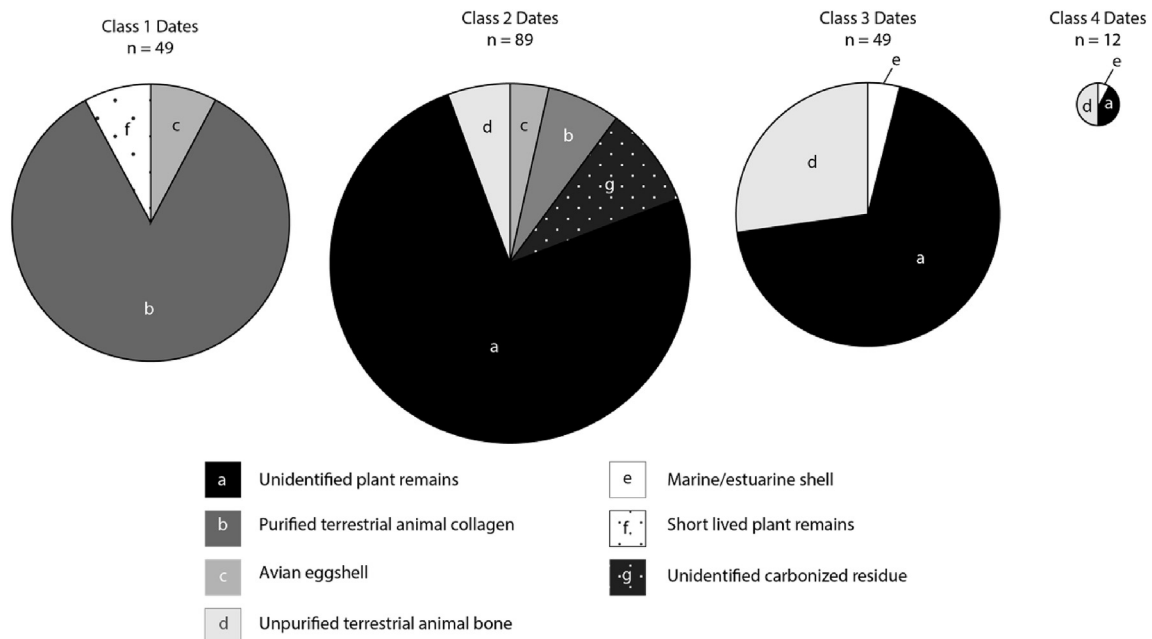


Fig. 3. The material type composition of our four rank classes. Diameters of circles are proportional to the square root of n. (Dataset S1) (Figure adapted from Wilmshurst et al. (2011)).

2002) and calibrated with the Marine13 curve (Reimer et al., 2013). Given this conservative ΔR marine correction, we added “1” to their precision ranking (Fig. 2).

2.4. Statistical analyses

We used the compiled ^{14}C dataset from Madagascar only for arrival event estimation, because the available Madagascar ^{14}C dataset is too small for estimating relative changes in human population size. In studies on the sensitivity of this proxy to sample size, Williams (2012) recommends using a minimum of 500 dates and Michczyńska and Pazdur (2004) suggest that at least 780 dates should be used. Our database includes only 199 dates, and a minority of these can be confidently considered associated with past human presence. Because of this limited sample size, changes in the frequency of dates through time in our dataset are more likely the product of taphonomic bias and researchers' site-specific ^{14}C priorities than the product of relative changes in past human population.

Using the calibrated dataset and both Bayesian and classical frequentist statistical approaches (described below), we estimated colonization events in Madagascar according to ecoregion (Burgess et al., 2004) and evidence type (i.e. introduced species, cutmarks, or artifact/feature). The earliest date associated with human presence is the maximum likelihood estimator of the true colonization event, but this estimator is biased, because the material record is fragmentary (Strauss and Sadler, 1989). Approaches to the problem of colonization event estimation build inference about the true event based on the attributes of the series of ^{14}C dates that follow the event.

To construct classical confidence intervals for colonization events, we use the Gaussian-resampled inverse-weighted McInerny (GRIWM) approach of Bradshaw et al. (2012) in R. In a sensitivity analysis of eight classical frequentist statistical approaches to the problem of event estimation based on radiometric dates, Saltré et al. (2015) found that the GRIWM approach had the highest accuracy. This approach starts with the assumptions that 1) radiometric errors are approximately normally distributed, and 2) sample record density is a proxy for population density. Based on the first assumption, the GRIWM approach incorporates measurement uncertainty by resampling dates from the probability distribution associated with each measurement. The second assumption is problematic due to variation through time in both fossil preservation and the ^{14}C calibration curve. However, the practical implication is that dates relatively close to an event of interest are relatively more important for estimating the time of the given event. Thus, the GRIWM approach weights observations inversely according to their temporal distance from the event of interest. A supplement by Saltré et al. (2015) provides the GRIWM R code, which was initially used to estimate extinction events. We applied this code to our data for arrival event estimation by first subtracting the mean calibrated age of each sample in a given sequence from the mean calibrated age of the oldest sample in this sequence. This effectively inverts the sequence before analysis (i.e. the oldest sample has an adjusted mean calibrated age of zero). Consequently, the GRIWM output is a confidence interval (CI) that follows the oldest adjusted sample (in the region of negative years before present), and this interval must be corrected back to actual years before present by subtracting the interval from the actual mean calibrated age of the oldest date in the sequence.

By using the “Boundary” function in OxCal 4.3 (Ramsey, 1995, a free online software: c14.arch.ox.ac.uk/), we follow the Bayesian approach of Buck and Bard (2007). This flexible approach incorporates measurement uncertainty and, in our case, starts with

the assumption that dateable material was deposited uniformly during the interval of interest. The prior assumption of uniform deposition rate is likely conservative, because, in reality, colonization typically involves a period of expanding population (and increasing rate of deposition).

3. Results

Most of the ^{14}C dated material in our database is associated with Late Holocene (<2000 cal BP) artifacts and features, but a few Early Holocene Class 1 dates are outliers associated with butchery of animals (Dataset S1). Two important Class 1 outliers are an *Aepyornis maximus* tibiotarsus from Christmas River, dated at two independent laboratories to 10432–10755 cal BP (UBA-31590; (Hansford et al., 2018)) and 10575–11094 cal BP (Hela-1774; (Muldoon et al., 2012)), and a *Mullerornis* sp. tibiotarsus from Lamboharana dated to 6282–6435 cal BP (UBA-29726; Hansford et al., 2018). Both bone specimens bear marks that Hansford et al. (2018) interpreted as signs of perimortem human modification. Although the stratigraphy of the Christmas River site is described (Muldoon et al., 2012), no cultural evidence beyond the butchered bone has been recorded and the archaeology of Lamboharana remains poorly described.

These outliers and later dates appear in Figs. 4 and 5 as points on a scale of mean calibrated years before present. Fig. 4 presents island-wide data and associated confidence intervals to estimate human arrival according to evidence type and quality class, while Fig. 5 presents all evidence type data and associated confidence intervals to estimate human arrival according to ecoregion and quality class. Classical frequentist (GRIWM) confidence intervals appear as diamonds (medians) and lines (95% confidence intervals). Bayesian confidence intervals appear as probability distributions (with 95.5% of each distribution marked in brackets). Bayesian confidence intervals tend to yield relatively conservative estimates for human arrival. In some cases, data from lower date quality classes extend confidence intervals further towards the present, and this is usually the consequence of limited sample sizes in relatively low quality classes.

Four features of our dataset make it important to carefully examine Early Holocene outliers.

First, the distribution of dates is heavily skewed toward recent time (range is > 10000 years, yet the median of the mean calibrated dates in our dataset is 793 cal BP, and 95% of the dates are younger than 3380–3560 cal BP), so outliers drive most of the variation in confidence intervals (Figs. 4–5).

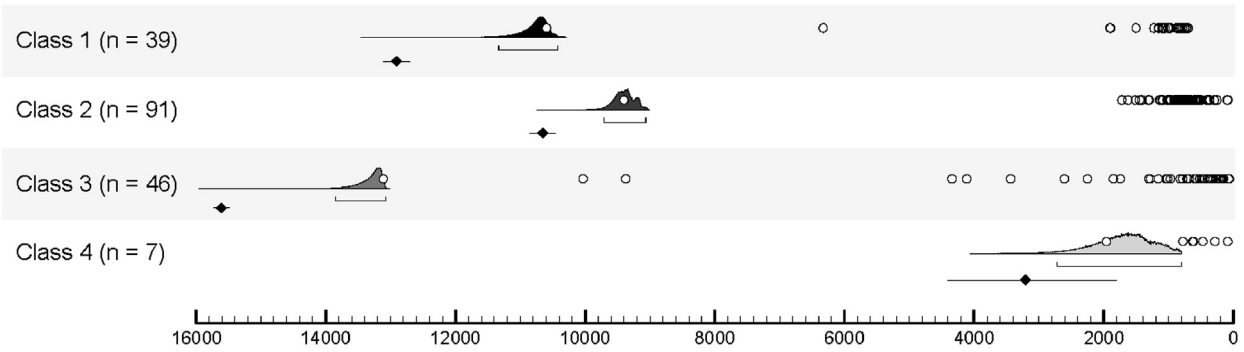
Second, outliers are not confined to low rank groups and thus cannot be attributed to poor data quality.

Third, Class 1 outliers are confined to two of Madagascar's five major terrestrial ecoregions: SW Madagascar's Spiny Thicket and Succulent Woodlands. Specifically, the Spiny Thicket and Succulent Woodlands Class 1 Bayesian 95.5% confidence intervals are 6283–6985 cal BP and 10439–13559 cal BP, respectively, which predate the Class 1 confidence intervals for other ecoregions by over 4000 years at least (Fig. 5). This pattern may highlight either significant missing data from other regions (as suggested by the relatively large number of dates associated with the early evidence from SW Madagascar) or a long delay between colonization events for different regions.

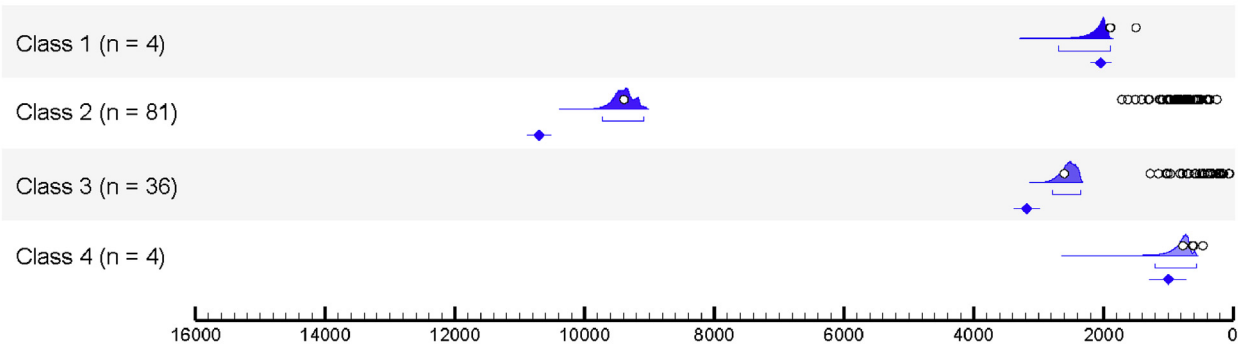
Fourth, Class 1 outliers are confined to one evidence type: butchery. Consequently, the Bayesian 95.5% CI associated with the Class 1 butchery dates (10431–11563 cal BP) predates by nearly 10,000 years the Bayesian confidence intervals for Class 1 artifact/feature dates (1885–2697 cal BP) and Class 1 introduction dates (1182–1683 cal BP). The aforementioned Christmas River and Lamboharana butchery data from Hansford et al. (2018) creates this

Islandwide Arrival Estimates

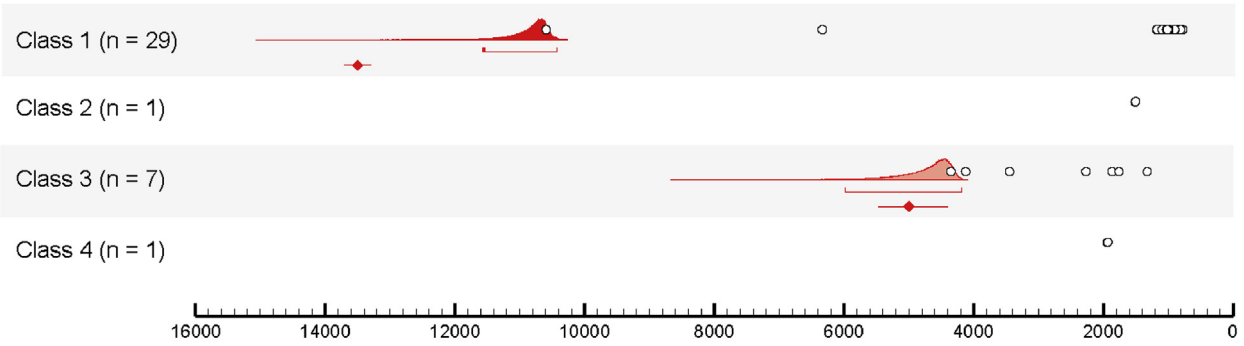
All Material Types



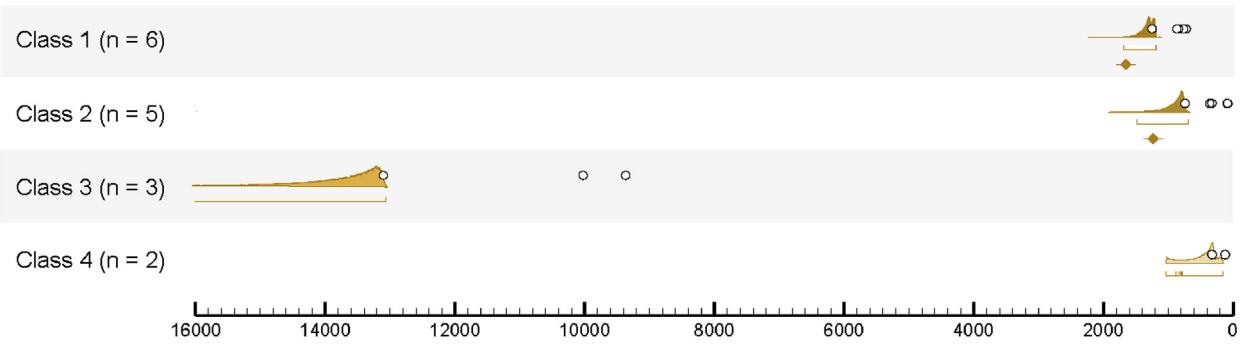
Artifacts/Features



Butchery



Introduction

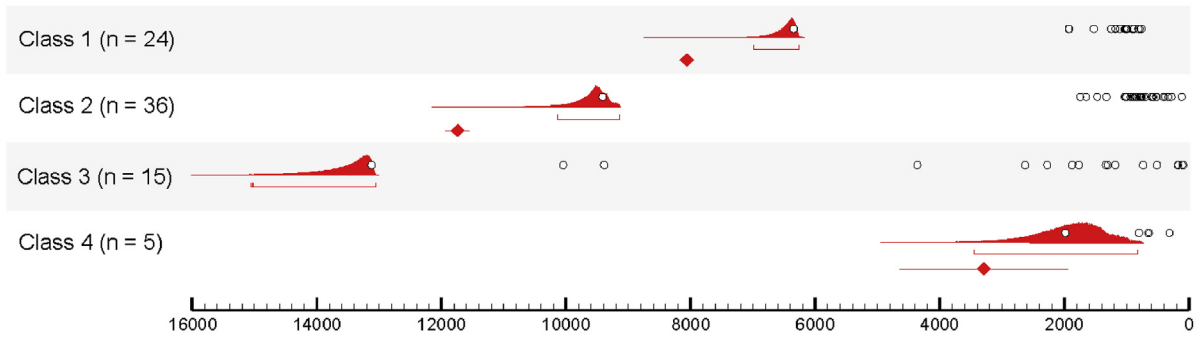


Mean Calibrated Years Before Present

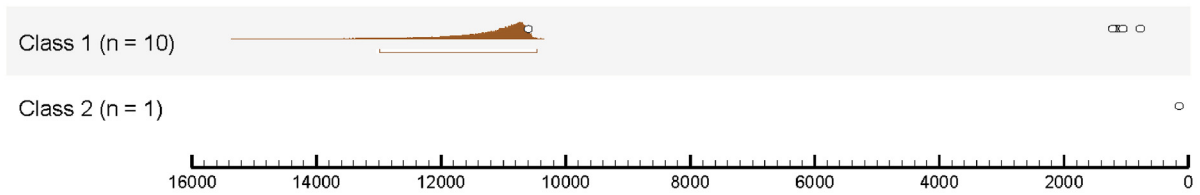
Fig. 4. Island-wide human arrival event estimates. Estimates are based on ^{14}C data according to evidence type (colored) and rank class. Within a given group, each white circle represents the mean calibrated age of a date that belongs to the group. Series of dates yield the associated confidence intervals (colored) for each group: Brackets under Bayesian posterior probability distributions span 95.5% of each distribution and diamonds and their associated lines mark the median and 95% confidence interval estimate from the classical frequentist approach. Classical frequentist confidence intervals are not given for groups with insufficient sample size ($n < 3$) and in cases where the interval extends to before 16,000 cal BP. Note that this figure does not include modern material that has been ^{14}C dated ($n = 13$), data that lack identified evidence type ($n = 5$, all from CDRC, Lyon), duplicate dates from the same material ($n = 1$, Hela-1774), and unbounded entries ($n = 1$, LY-3749).

Ecoregion Arrival Estimates

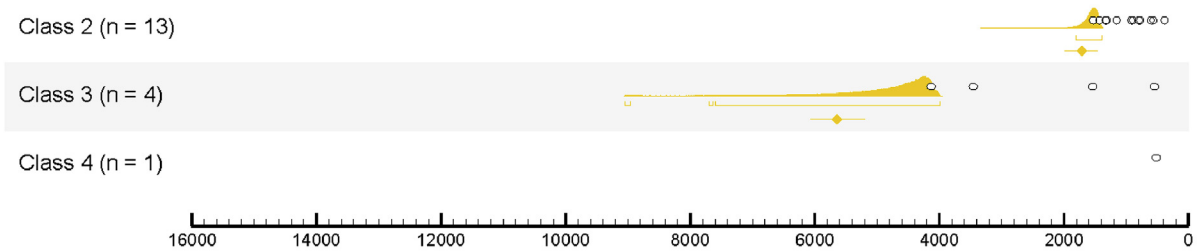
Spiny Thicket



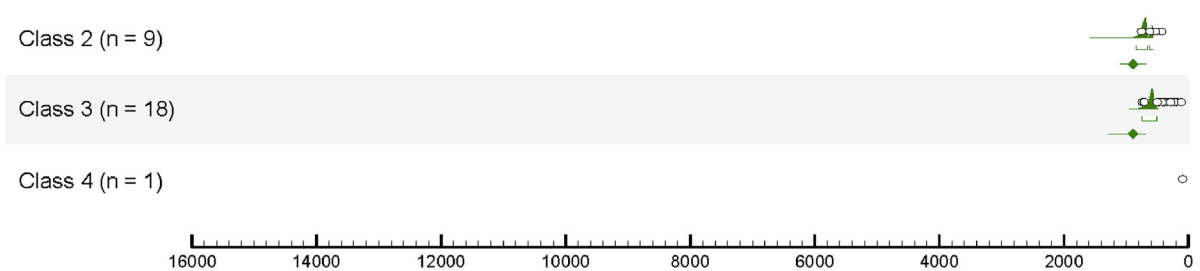
Succulent Woodland



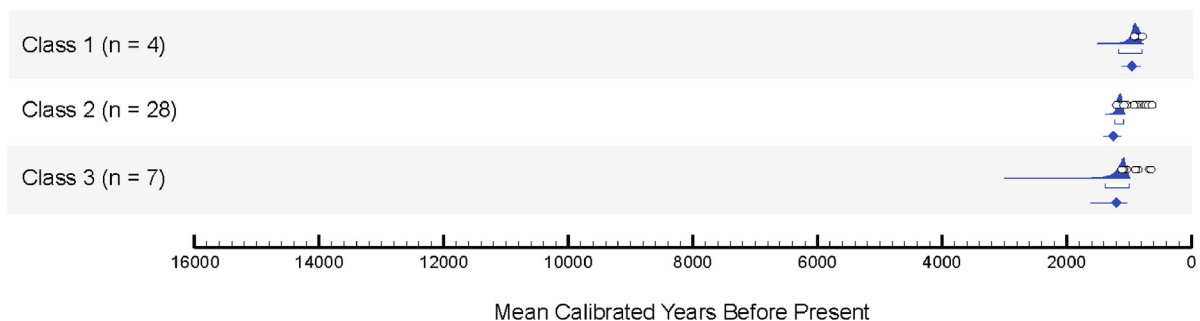
Dry Deciduous Forest



Central Highlands



Humid Forest



Mean Calibrated Years Before Present

Fig. 5. Ecoregion-specific human arrival estimates. Estimates are based on ^{14}C data according to ecoregion (colored) and rank class. Within a given group, each white circle represents the mean calibrated age of a date that belongs to the group. Series of dates yield the associated confidence intervals (colored) for each group: Brackets under Bayesian posterior probability distributions span 95.5% of each distribution and diamonds and their associated lines mark the median and 95% confidence interval estimate from the classical frequentist approach. Classical frequentist confidence intervals are not given for groups with insufficient sample size ($n < 3$) and in cases where the interval extends to before 16,000 cal BP. Note that this figure does not include modern material that has been ^{14}C dated ($n = 13$), data that lack identified evidence type ($n = 5$, all from CDRC, Lyon), duplicate dates from the same material ($n = 1$, Hela-1774), unbounded entries ($n = 1$, LY-3749), and dates from material of unknown sites in Madagascar ($n = 1$, UBA-19725).

difference, and this requires explanation. On one hand, early Class 1 evidence from butchery might be expected given that over 70% of Class 1 data comes from butchered bone. On the other hand, early butchery evidence is surprising since only one artifact/feature yielded an Early Holocene date, despite the fact that over 60% of all available radiocarbon data comes from artifacts and features. In this case, the earliest date from an artifact/feature comes from an *Aepyornis* eggshell fragment of uncertain association with human activity from the Tony rock shelter site in Velondriake in the Spiny Thicket ecoregion (OxA-34217, 9258–9545 cal BP; S1).

It is useful to consider how the absence of the Early Holocene outliers would affect confidence intervals that we use to estimate times for human arrival. Recall that, when all Class 1 dates from bone with butchery marks are considered, the Bayesian 95.5% CI is 10431–11563 cal BP. When the same group of Class 1 butchery dates is considered without the outliers, the Bayesian 95.5% CI is 1110–1225 cal BP. However, when Class 1 dates from all evidence types (i.e., artifacts/features, butchery, and introductions) are considered together without the two butchery outliers (UBA-31590 and UBA-29726), the Bayesian 95.5% CI is 1879–2063 cal BP. The fact that the CI for the entire Class 1 group is older than the CI for the Class 1 butchery group can be explained by the artifact and introduction dates in Table 1, which are all older than the oldest Class 1 butchery date after the outliers are excluded (*Archaeolemur majori* from Manombo Tulear, CAMS 142604, 1075–1269 cal BP).

4. Discussion

Until recently, cutmarks on bone of endemic lemurs and pygmy hippos provided the main support for the claim that humans colonized Madagascar by at least ~2300 cal BP (Burney et al., 2004; Godfrey and Jungers, 2003; Gommery et al., 2011; MacPhee and Burney, 1991; Perez et al., 2005). Researchers have recently questioned the anthropogenic and perimortem status of many of the cutmarks on these ¹⁴C dated bones (Anderson et al., 2018a, 2018b), yet cutmarks continue to play an important role in discussions of early human presence on Madagascar (Hansford et al., 2018). The fact that most modified bones come from poorly documented or naturally accumulating deposits (e.g. Anjohibe, Burney et al., 1997) weakens the association of some of these marked bones with human activity and highlights the need for additional fieldwork. Still, existing Class 1 butchery data suggest that humans were present on Madagascar during the Early Holocene, even if such an early arrival did not result in permanent settlement.

The introduction of animals and plants to Madagascar by people represents one of the most significant anthropogenic modifications of the island's ecosystems. Introduced taxa (esp. mammals and freshwater fish) currently represent over ~15% of some vertebrate classes (Kull et al., 2012). A small number of introduced animal remains provide a complementary line of evidence for early human presence on Madagascar. All of the dated bones of introduced animals that are clearly associated with humans (e.g. dogs, cats, and

rats) are from the Late Holocene (Crowley, 2010; Crowley et al., 2017; Crowley and Samonds, 2013). However, guinea fowl (*Numida meleagris*) and pied crow (*Corvus albus*) remains may support an early human presence on the island (Godfrey et al., 2019). While the status of these species as anthropogenic introductions remains uncertain, Walsh (2007) used linguistic evidence to suggest that early visitors to Madagascar brought the guinea fowl from mainland Africa, and the pied crow is known to be a ship stow-away (Goodman et al., 2013). Most guinea fowl remains on Madagascar are less than 1000 years old (Radimilahy, 1998; Rakotozafy, 1996; Rakotozafy and Goodman, 2005), but a few specimens from Ankililelo date to the terminal Pleistocene and Early Holocene (13051–13229 to 9286–9491 cal BP, Goodman et al., 2013). Given other evidence for an Early Holocene human presence in Madagascar, the possibility that guinea fowl and pied crow are anthropogenic introductions should be further investigated. Lake sediment proxies such as the abundance of spores of the dung-loving fungus *Sporormiella* spp. can also help constrain past species introductions (Burney et al., 2003). Future work should prioritize directly dating remains from introduced species to confirm whether these proxy records are, in fact, indicative of the presence of introduced versus endemic herbivores (Douglass and Zinke, 2015; Raper and Bush, 2009).

Introduced plants on Madagascar represent close to 10% of the island's flora today (Moreau et al., 2012), but these introductions have received relatively little archaeological and paleoecological attention (Beaujard, 2017). The only introduced plant that has been ¹⁴C dated is *Oryza sativa* (rice), which is one of the most economically important crops on Madagascar today and an indication that the Austronesian expansion reached the island. The earliest direct evidence for rice on Madagascar, however, is relatively late (801–934 cal BP, Crowther et al., 2016). Pollen in lake sediments record the past presence of other potential plant introductions on Madagascar. For example, *Cannabis sativa* (hemp) pollen exists in sediments from Lake Tritrivakely that date to ~2200 cal BP (Burney, 1987a; Gasse and Van Campo, 1998), and *Ricinus communis* (castor bean) pollen exists in sediments from Lake Kavitaha that date to ~1000 cal BP (Burney, 1987b), but it is unclear whether these species are human introduced (Beaujard, 2007). More work with ancient macrobotanical remains is required to clarify the early history of plant introductions. Finally, past human presence on Madagascar has also been inferred from pollen, charcoal, and stable isotope records of vegetation change (Burney, 1987b, 1993; Burns et al., 2016; Virah-Sawmy et al., 2016). For example, Burns et al. (2016) used speleothem stable isotope records and uranium-thorium (²³⁴U and ²³⁰Th) disequilibrium dating to infer human presence around Anjohibe Cave in northwestern Madagascar ca. 1100 years ago due to a rapid transition to a grass dominated landscape during a period of relatively mesic conditions. More work is needed across different ecoregions on Madagascar on long term variability in climate, vegetation patterns, and natural and anthropogenic fire regimes to verify how widespread these trends

Table 1
Early Class 1 dates. Class 1 dates associated with introduced species, artifacts, and features that are older than the oldest class 1 butchery date (excluding the data from Hansford et al. (2018)). Note that all dates were calibrated using SHCal13 (Hogg et al., 2013).

Site	Evidence Type	Material	¹⁴ C Lab Code	Cal BP	Citation
Tony, Velondriake	artifact/feature	avian eggshell	OxA 34215	1879–2097	This paper
Tony, Velondriake	artifact/feature	avian eggshell	OxA 34216	1875–2051	This paper
Tony, Velondriake	artifact/feature	avian eggshell	OxA-34274	1529–1690	This paper
Lakaton'i Anja	artifact/feature	<i>Palaeopropithecus</i> sp. cf. <i>maximus</i> bone collagen	Beta-359909	1409–1545	This paper
Lakaton'i Anja	artifact/feature	<i>Palaeopropithecus</i> sp. cf. <i>maximus</i> bone collagen	Beta-359225	1307–1514	This paper
Lakaton'i Anja	artifact/feature	<i>Palaeopropithecus</i> sp. cf. <i>maximus</i> bone collagen	Beta-359226	1305–1412	This paper
West Mikoboka Plateau Cave	introduced species	<i>Rattus rattus</i>	CAMS 147034	1270–1344	Crowley et al. (2017)

might be.

The vast majority of ^{14}C dated archaeological features and artifacts are less than ca. 1000 years old. The small NSS2 rock shelter in the Velondriake region of the SW coast, however, yielded worked marine shell dated to 3084–3362 cal BP (D-AMS 012442, Douglass, 2016a), and Dewar et al. (2013) identified traces of older human activity in the far north of Madagascar through Optically-Stimulated Luminescence (OSL) dating of rock shelter deposits. The scarcity of relatively early ^{14}C -dated artifacts and features may reflect the greater visibility of later sites. Large settlements and urbanism developed along the coasts only after 1000 cal BP (Dewar et al., 2013; Ekblom et al., 2016; Pearson, 2010; Radimilahy, 1997, 1998; Wright et al., 1993, 1996), while the earlier record of mobile foragers is ephemeral and has only recently been the focus of targeted investigations (Dewar et al., 2013; Douglass and Zinke, 2015). Archaeological fieldwork that is prepared to recognize the cryptic records left by small-scale, mobile communities must be a priority to further elucidate Madagascar's pre-urban history.

Interpretations of existing genetic and linguistic data do not preclude an Early Holocene human presence on Madagascar (most likely migrants from the African continent), particularly considering the possibilities of occasional visits, low population densities, and failed colonization attempts. Studies of modern genetic diversity on Madagascar suggest that an early Malagasy population split from south Bornean populations no later than 2000–3000 BP with a subsequent contribution from mainland African populations no later than 1500 BP (Pierron et al., 2017). A dramatic increase in the effective population size of humans likely occurred at ca. 1000 BP (Pierron et al., 2017), which is consistent with archaeological records of the expansion of settlements and the rise of urbanism in coastal Madagascar. Though debate is ongoing, linguists estimate that Malagasy diverged from languages in the Barito Valley of Borneo after 2000 BP (Adelaar, 1995; Dahl, 1951).

In summary, the recently documented cutmarks on elephant bird bone (Hansford et al., 2018), the possible early introductions of two bird species (Goodman et al., 2013), and an increasingly recognized mid-Holocene archaeological record of past hunter/forager activity (Dewar et al., 2013; Douglass, 2016b) suggest that humans were present in Madagascar well before 2000 cal BP.

5. Conclusion

Madagascar's colonization has been a hotly debated question in archaeology for decades. Recent contributions to this debate have yielded estimates of initial settlement that diverge by as much as ca. 9000 years (Anderson et al., 2018b; Hansford et al., 2018): making Madagascar's colonization chronology the most poorly resolved of any island settled within the reliable range of ^{14}C dating. In this paper, we have presented the first assessment of Madagascar's settlement chronology that evaluates the reliability of existing ^{14}C measurements using a systematic statistical approach. Our assessment strongly supports the presence of people on Madagascar by 2000 cal BP and suggests that an Early Holocene arrival is possible, despite a lack of contextual information to provide insights into the nature and permanence of such an early presence.

While this study supports the possibility of an Early to Mid-Holocene arrival of humans to Madagascar, the early human history of the world's fourth largest island remains frustratingly cryptic. The lack of data on human cultures and activities on Madagascar during the Early and Mid-Holocene has consequences for how we understand the rate and process of Late Holocene changes, such as megafaunal extinctions. Our study suggests humans and megafauna overlapped in Madagascar for at least 1500 years, and an Early Holocene arrival implies an overlap with all

known megafauna for ca. 9000 years. Such a long period of potential overlap between human and megafauna communities contrasts the Madagascar case to other island extinction trajectories worldwide, making it more comparable to rare examples of protracted extinctions (Jones et al., 2008) than to cases of rapid extinction post-human arrival (e.g., Steadman, 2006).

Overcoming the lack of resolution on Madagascar's Early and Mid-Holocene settlement will require survey and excavation methodologies suitable for investigating ephemeral hunter/forager sites, continued work on remains of introduced plants and animals to better infer population histories and timing of introductions, ongoing assessments of cutmarks and stratified deposits associated with existing ^{14}C data, and integrated investigations of archaeological sites and associated climate and paleoecological records to better understand subtle anthropogenic changes in environment.

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Author contributions

KD and SH compiled ^{14}C dates, conducted analyses and drafted the manuscript. All additional co-authors contributed previously unpublished dates and commented on the manuscript.

Competing interests

We declare no competing interests in the preparation and publication of this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2019.105878>.

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