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A model-based approach to the tempo of "collapse": The case of Rapa Nui (Easter Island)

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ABSTRACT

Rapa Nui (Easter Island, Chile) presents a quintessential case where the tempo of investment in monumentality is central to debates regarding societal collapse, with the common narrative positing that statue platform (*ahu*) construction ceased sometime around AD 1600 following an ecological, cultural, and demographic catastrophe. This narrative remains especially popular in fields outside archaeology that treat collapse as historical fact and use Rapa Nui as a model for collapse more generally. Resolving the tempo of "collapse" events, however, is often fraught with ambiguity given a lack of formal modeling, uncritical use of radiocarbon estimates, and inattention to information embedded in stratigraphic features. Here, we use a Bayesian model-based approach to examine the tempo of events associated with arguments about collapse on Rapa Nui. We integrate radiocarbon dates, relative architectural stratigraphy, and ethnohistoric accounts to quantify the onset, rate, and end of monument construction as a means of testing the collapse hypothesis. We demonstrate that *ahu* construction began soon after colonization and increased rapidly, sometime between the early-14th and mid-15th centuries AD, with a steady rate of construction events that continued beyond European contact in 1722. Our results demonstrate a lack of evidence for a pre-contact 'collapse' and instead offer strong support for a new emerging model of resilient communities that continued their long-term traditions despite the impacts of European arrival. Methodologically, our model-based approach to testing hypotheses regarding the chronology of collapse can be extended to other case studies around the world where similar debates remain difficult to resolve.

1. Introduction

Monumental architecture, such as earthen mounds, massive stone circles, burial complexes, and temples trace the history of collaborative achievements by human communities over the last ca. 10,000 years. Because building these structures necessarily required group-level cooperation, their appearance, elaboration, and cessation at different times and places around the world are useful as archaeological evidence for changes in social organization and complexity (Abrams, 1989; DeMarrais et al., 1996; Kirch, 1990; Marcus and Flannery, 2004; Trigger, 1990). Yet, given the wide range of environmental and social conditions under which these phenomena emerge, explaining the dynamics of monument construction in different world regions remains a central challenge to archaeologists (DiNapoli et al., 2019; Howey et al., 2016). One step toward progress in this effort requires the establishment of reliable chronologies that provide probabilistic estimates for when monumentality begins, the timing of investments in these features made over the duration of their use, and the point at which construction activities cease. It is through such information that archaeologists can document events associated with increases in organizational complexity, cultural resilience in the face of environmental or demographic changes, or societal collapse.

Though the definition and process of 'collapse' have long been debated (e.g., Butzer and Endfield, 2012; Kirch and Rallu, 2007; McAnany and Yoffee, 2010; Middleton, 2012; Scheffer et al., 2012; Schwartz and Nichols, 2006; Strunz et al., 2019; Tainter, 1988, 2006; Yoffee and Cowgill, 1988), most scholars agree that these kinds of events commonly involve the end or decline in some kind of activity, whether it be changes

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in settlement patterns, like depopulation of political centers, declines in focal aspects of religious and social activity, such as the end of monument construction, or other factors (e.g., Dunnell and Greenlee, 1999; Middleton, 2017; Turner and Sabloff, 2012). In a recently proposed series of 'grand challenges' for archaeology, Kintigh et al. (2014a, 2014b) highlight collapse as a central issue in the discipline and stress the need for broadly applicable ways of characterizing societal declines or transitions. One basic, but critical, component for resolving these issues concerns the chronology of these events in absolute and relative terms (Butzer and Endfield, 2012; Scheffer, 2016; Scheffer et al., 2012). Some recent studies have approached this issue using summed probability distributions of radiocarbon dates (e.g., Downey et al., 2016; Hoggarth et al., 2016; Shennan et al., 2013). Here, using the hypothesized 'collapse' of Rapa Nui (Easter Island) monument construction as a case study, we present an alternative approach that makes use of Bayesian model-based testing of hypotheses for collapse that considers the onset, tempo, and cessation of archaeological events. Our Bayesian approach combines radiocarbon determinations, relative chronological information from architectural stratigraphy, and ethnohistoric accounts with the recently developed 'tempo plot' technique (Dye, 2016) to provide rigorous, model-based estimates for when monument construction begins, the rate of change in monument construction events, and the most likely timing for the cessation of these activities.

Our results provide a key line of evidence contradicting the collapse narrative for Rapa Nui and thus calls into question a broad range of interdisciplinary research that uses the island as a model for societal decline more generally. Though we approach the issue of collapse on Rapa Nui with reference to chronologies of monument construction, we discuss how our methodological approach to testing hypotheses regarding the chronology of collapse can be extended to other case studies around the world where similar debates remain difficult to resolve.

2. Background: Rapa Nui (Easter Island)

Rapa Nui (Easter Island, Chile, Fig. 1) presents a quintessential case in world history where the tempo of intensified monument construction is central to debates regarding societal collapse. This small (164 km^2) and isolated island is situated in the southeastern margin of East Polynesia, some 3000 km from South America and nearly 2000 km from the nearest inhabited island. Current estimates suggest that Polynesian voyagers initially colonized the island around the 13th century AD (e.g., Hunt and Lipo, 2008, 2006; Lipo and Hunt, 2016; Wilmshurst et al., 2011). At some point after this event, islanders began constructing megalithic platforms (*ahu*) and carving and transporting multi-ton statues (*moai*). These monuments subsequently served as a major focal point for social and ritual activity of Rapa Nui's pre-contact communities (Martinsson-Wallin, 1994; Métraux, 1940; Morrison, 2012; Stevenson, 2002). Despite its size and remote location, the present archaeological record of Rapa Nui boasts hundreds of *ahu* and nearly 1000 *moai*.

The role of monument construction over the course of Rapa Nui's culture history has been the subject of prolonged speculation and debate. *Ahu* construction and elaboration are commonly used as evidence for increasing social complexity and fission-fusion patterns among Rapa Nui's social groups (Stevenson, 2002, 1997; 1986; Wallin and Martinsson-Wallin, 2008). In addition, numerous archaeological narratives for the island posit that an accelerated pace of monument construction, during the "Ahu Moai" phase, led to an environmental and demographic collapse around the 17th century. A core component of this narrative is the rapid destruction of monuments and end of *ahu* and *moai* construction, a time period termed the "Huri Moai," literally 'statue toppling,' phase (Bahn and Flenley, 1992, 2017; Diamond, 2005; Flenley and Bahn, 2003; Kirch, 1984, 2017; Smith, 1961a). While a popular account, the lack of empirical evidence for many aspects of this narrative (Hunt, 2007; Hunt and Lipo, 2011; Mulrooney, 2013; Mulrooney et al., 2010, 2009) has led some to argue that monument construction was instead a key factor in the long-term persistence of pre-contact communities that only terminated as a consequence of changes following the arrival of Europeans (Boersema, 2015; DiNapoli et al., 2019, 2018; Hunt and Lipo, 2018, 2011; Lipo et al., 2018; Mulrooney et al., 2010; Peiser, 2005). Despite these criticisms, the notion that the late pre-contact period on Rapa Nui was a time of severe cultural and demographic changes remains popular (e.g., Bahn and Flenley, 2017; Kirch, 2017; Puleston et al., 2017; Rull, 2018, 2016; Rull et al., 2018; Scheffer, 2016). Indeed, the narrative of collapse on Rapa Nui is still persistently used in fields outside archaeology as a model for societal collapse, treating the supposed events of the 'Huri Moai' phase as historical fact (e.g., Akhavan and Yorke, 2019; Anderies, 2000; Basener and Ross, 2004; Basener and Basener, 2019; Bologna and Flores, 2008; Brander and Taylor, 1998; Brandt and Merico, 2015; Cazalis et al., 2018; D'Alessandro, 2007; Dalton et al., 2005; Dalton and Coats, 2000; de la Croix and Dottori, 2008; Dockstader et al., 2019; Erickson and Gowdy, 2000; Pezzey and Anderies, 2003; Reuveny, 2012; Reuveny and Decker, 2000; Roman et al., 2017; Takács et al., 2019; Uehara et al., 2010).

Monumental architecture is central to explanations of Rapa Nui culture history and the proposed collapse of its pre-contact society. Yet, the chronology of *ahu* construction remains poorly resolved, leading to uncertainty in evidence such that debates are difficult to settle. For example, while we can currently say that monument construction was

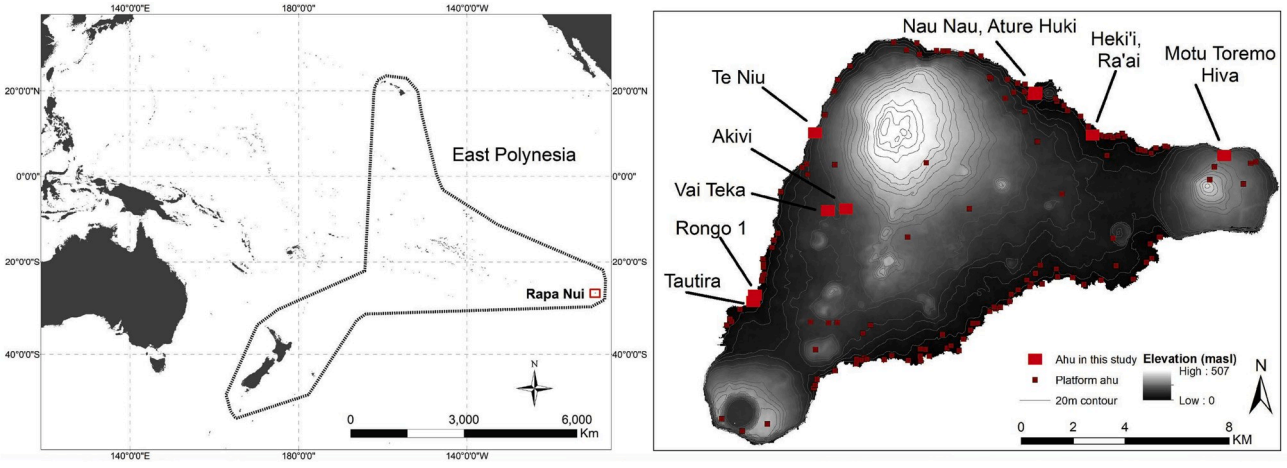

Fig. 1. Rapa Nui and East Polynesia. East Polynesia (left), and Rapa Nui showing the locations of all documented platform *ahu* as well as those analyzed in this study (right).

widespread during some component of Rapa Nui's history, further details about the onset, rate, and duration of these activities are ambiguous. Moving past this generalization requires developing chronological models for these events involved in monument construction activities. Like with many chronological issues in archaeology, formal Bayesian models provide a useful tool to better resolve temporal patterns of monument construction (e.g., Carter et al., 2019; Chirikure et al., 2013; Culleton et al., 2012; Dye, 2016, 2012; Schulz Paulsson, 2019).

2.1. Previous chronologies for ahu construction

Heyerdahl and Ferdon's (Heyerdahl and Ferdon, 1961) Norwegian archaeological expedition to Rapa Nui in the 1950s provided the first modern attempts to build an absolute chronology for *ahu* construction. They built their chronology based on stratigraphic evidence derived from the excavation of numerous *ahu* complexes as well as ^{14}C dates from *ahu* Vinapu, Te Peu, and several other important sites on the island. Based on this evidence, they argued that the island experienced an early period of *ahu* construction around ca. AD 800 and that this activity continued until AD 1600s (Smith, 1961b). Following Heyerdahl and Ferdon, Ayres (1971) offered the next absolute chronology based on ^{14}C dates from excavations at *ahu* Tahai and Ko te Riku. Evidence from his excavations suggested that initial *ahu* construction activities began around AD 700. Mulloy and Figueroa (1978) later proposed that the initial construction of *ahu* Akivi and Vai Teka did not begin until ca. AD 1450. Using a large suite of obsidian hydration dates from several south coast *ahu*, Stevenson (1986, pp. 74–76) argued that the initial construction of *ahu* Vaihu, Akahanga, and Ura Uranga te Mahina took place between AD 1301–1400, with additional platform *ahu* construction and rebuilding episodes continuing into the late 1600s. Stevenson (1997, pp. 8–13) later altered this chronology using a different hydration rate constant to argue that initial construction occurred as early as ca. AD 1000, with platform construction limited after ca. AD 1500–1600. In their reviews of early ^{14}C dates from several *ahu* across the island, including *ahu* Nau Nau and Ature Huki (Skjølsvold, 1994), Heki'i (Martinsson-Wallin, 1998; Martinsson-Wallin and Wallin, 1998), Ra'ai (Martinsson-Wallin and Wallin, 2000), Viri o Tuki (Huyge and Cauwe, 2005), Motu Toremo Hiva (Cauwe et al., 2010, 2006), Vinapu (Martinsson Wallin, 2004), Rongo (Huyge and Cauwe, 2002), and Tautira (Martinsson-Wallin and Crockford, 2002), Wallin and colleagues (Wallin et al., 2010, p. 43; Wallin and Martinsson-Wallin, 2008, p. 154) suggest that initial construction of these complexes likely occurred around AD 1250–1400, but possibly as early as AD 1100–1200. In a later analysis of a select sample of ^{14}C dates from *ahu*, Martinsson-Wallin et al. (2013) use summed probability distributions (SPD) to estimate the onset and cessation of *ahu* construction. In their visual interpretation of the *ahu* SPD, they suggest that *ahu* complexes "were securely in place on Rapa Nui by ca. AD 1300–1400" and claimed that a 'destruction phase' for large platform *ahu* occurred around AD 1600 (Martinsson-Wallin et al., 2013, pp. 417, Figure 7). This argument for a "[d]egeneration of ceremonial sites" (Wallin and Martinsson-Wallin, 2008, p. 154) during a destruction phase for platform *ahu* around AD 1600 assumes a transition from the "Ahu Moai" phase to the "Huri Moai" phase in Rapa Nui culture history (Kirch, 1984, 2017; Smith, 1961a; cf. Mulrooney et al., 2009; Lipo and Hunt, 2009).

These previous dating programs have provided valuable data and working hypotheses for monument construction and testing the collapse narrative on Rapa Nui. These estimates for initial *ahu* construction are limited, however, given that they are not based on formal statistical models but on *ad hoc* visual approximations of the calibrated date lists, or in the case of Martinsson-Wallin et al. (2013), visual approximations of an SPD. Given contemporary concerns over choices of samples for generating radiocarbon dates (Hunt and Lipo, 2006; Wilmshurst et al., 2011; Allen and Huebert, 2014; Rieth and Athens, 2013; Spriggs and Anderson, 1993; cf. Schmid et al., 2018), the now well-understood uncertainties with visual interpretations of dates, and a multitude of issues with simple visual inspection of SPD curves (Bayliss et al., 2007; Contreras and Meadows, 2014; Crema et al., 2016; Dye, 2016; Timpson et al., 2014), these chronologies for initial *ahu* construction are in need of re-evaluation. Previous syntheses of ^{14}C data from *ahu* have also not included the rigorous dating program by Wozniak (2003) at *ahu* Te Niu. Furthermore, the timing of the cessation of platform *ahu* construction is poorly understood, given the lack of formal modeling and sporadic and limited historical accounts from the 18th century. Bayesian chronological modeling provides a promising alternative for examining the chronology of *ahu* on Rapa Nui given the island's short chronology and highly overlapping radiocarbon probability distributions, as well as the approach's explicit aim of incorporating prior information about relative construction components from the dated sequences and ability to formally model the timing of events that are otherwise not directly dated (Dye, 2016, 2012; Schulz Paulsson, 2019).

3. Materials and methods

3.1. Objectives

Here, we use a sample of previously published ^{14}C determinations in concert with relative *ahu* construction events to build a series of Bayesian models to estimate the onset and later tempo of *ahu* construction. We construct these models using OxCal v.4.3.2 (Bronk Ramsey, 2017). For clarity, we capitalize and italicize OxCal commands (e.g., *Phase, Sequence,* etc.). We use the ArchaeoPhases package (Philippe et al., 2019) to create a tempo plots of *ahu* construction activity. Our primary objectives are: (1) to estimate how soon after the colonization of Rapa Nui initial monument construction began; and (2) to estimate the duration of *ahu* construction events, including initial platform construction and the timing of later investments, such as how far they extend into the pre-contact and/or early historic eras as a means of testing the claim that *ahu* construction ceased following a pre-contact collapse. These objectives require that we have a reliable estimate for initial colonization and select samples that most closely relate to *ahu* construction and use.

3.2. Colonization models

We use existing radiocarbon determinations from the published literature to provide refined Bayesian estimates for Rapa Nui colonization. We start by using ^{14}C samples with a conventional radiocarbon age (CRA) $\geq$ 650 BP not from *ahu* contexts (see Supplementary Materials; Table S1). Our use of a $\geq$650 BP threshold provides a focus on samples that conceptually relate to the early pre-contact/colonization era, such that the colonization estimate is not biased by younger ^{14}C samples that are unrelated to colonization (Mulrooney et al., 2011). We do not include samples from monumental architecture contexts in the colonization models as these determinations are included in the *ahu* models. We group the ^{14}C samples into a single *Phase*, with the start *Boundary* providing the colonization estimate. We built two colonization models using ^{14}C samples from archaeological contexts: one with only short-lived plant remains (n = 9), and a second with these nine short-lived samples and 19 unidentified charcoal samples. For the second model, we apply a *Charcoal Outlier* parameter to assess the influence of unidentified charcoal samples on the precision of our colonization estimate (Bronk Ramsey, 2009; Dee and Bronk Ramsey, 2014; Schmid et al., 2018).

3.3. Relative construction model for platform ahu

Rapa Nui islanders constructed multiple classes of ritual stone structures that are collectively referred to as *ahu*. Here, we focus our study on the ca. 150 known platform *ahu*, also called 'image-*ahu*' or *ahu moai*, which are the largest and most common form of pre-contact *ahu* (Martinsson-Wallin, 1994). The term image-*ahu* denotes that many of

these monuments have one or more *moai* statues, though this is not always the case. Their central architectural feature is a rectangular platform with a dressed stone or closely aligned back wall. These central platforms typically contain combinations of auxiliary features, such as linear alignments of stacked stone projecting laterally from the platform (termed 'wings'), a ramp descending from the front of the platform that is paved with water-worn boulders (*poro*), a pavement/plaza of *poro* stone in front of the ramp, a rectangular embankment enclosing the plaza, and a crematorium (which generally is attached to the back side of the platform). *Ahu* also often contain burial features within different components of the structure. Lastly, their visible attributes and stratigraphic information from archaeological excavations have shown that most platform *ahu* were continually added to over the years with multiple building events (Martinsson-Wallin, 1994; Skjølsvold, 1994; Smith, 1961a). These different architectural features allow for building relative chronologies of *ahu* construction that can be used as informative priors in Bayesian models. Specifically, if we consider the different construction elements as depositional events (Dye, 2016, 2010), then the central platform is logically the initial construction component, as the other components are built off of it and, therefore, wings, ramps, crematoria, etc., must logically post-date platform construction (See Fig. 2 for a model schematic of a typical platform *ahu*). In most instances the stratigraphic relationships between different architectural elements confirm this generalized sequence (e.g., wing structures that abut the central platform).

3.4. Models for ahu construction

To build a chronology for events associated with *ahu* construction, we create a series of multi-phase Bayesian models designed to estimate initial platform construction, the timing of later additions, and end of construction for several *ahu*. These models incorporate radiocarbon determinations, relative architectural stratigraphy, and ethnohistoric accounts as informative priors. Using published contextual information from excavations at *ahu*, we group ^{14}C determinations into *Phases* related to the construction of the central *ahu* platform using three classes of events: (1) samples related to events from contexts below the platform are treated as *termini post quos* (TPQs), which we term 'pre-platform construction' phases; (2) samples contextually associated with our target event of platform construction are classified as 'platform construction' phases; and (3) samples from any of the auxiliary features (e.g., ramps, wings) that post-date platform construction are *termini ante quos* (TAQs), which we term 'post-platform' phases. In these models, the

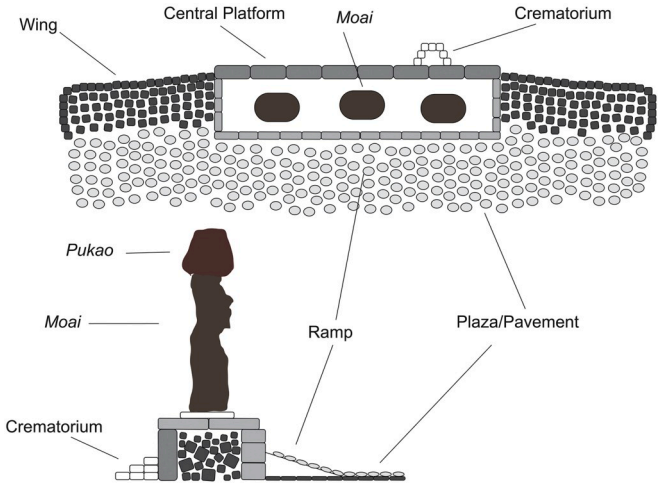

Fig. 2. Model schematic of a platform *ahu*. Schematic of a typical platform *ahu* showing a plan view (top) and cross-section (bottom). Figure adapted from Martinsson-Wallin (1994) and Skjølsvold (1994).

determinations from pre-platform, platform, and post-platform events are grouped into unordered *Phases* within an ordered *Sequence*. We also use the *Boundary* start estimate from the colonization model to constrain the estimates for platform construction, as initial *ahu* construction must logically post-date colonization. Lastly, for the end of the *Sequence* we input a uniform calendar date range (of AD 1838–1868 (*Date(U(1838, 1868))* in OxCal) to serve as a cutoff point for the construction estimates. This choice of AD 1838–1868 is based on historic European accounts of the last time a *moai* statue was recorded as still standing upright on an *ahu* platform, which serves as a conservative estimate for the time period after which we assume no platform *ahu* were built (see section 3 of Supplementary Materials for an extended discussion of this rationale). This final parameter simply serves to constrain the right side of the calibrations in the post-platform phase. The general form of these *ahu* models is: Colonization > TPQ (pre-platform) > Target (platform construction) > TAQ (post-platform) > AD 1838–1868.

We construct multi-phase models for each individual *ahu* with ^{14}C determinations from either (a) TPQ, target, and TAQ; (b) TPQ and target, (c) target and TAQ, or (d) TPQ and TAQ events. Models of types (a), (b), and (c) are constructed as Contiguous *Sequences*, and the start of the target event *Boundary* provides the estimate for initial *ahu* construction, the start *Boundary* for the post-platform phase provides the estimate for later construction events, and the end *Boundary* estimates the end of *ahu* construction activities. Models of type (d) are constructed as Sequential *Sequences*, and we insert a *Date* command between the end *Boundary* of the pre-platform *Phase* and the start *Boundary* of the post-platform *Phase* to estimate the start of platform construction. We use the *Difference* query to estimate the temporal lag between the colonization *Boundary* and the start of construction for each *ahu*.

3.5. Model-based estimates for the duration of ahu construction

To explore the duration of *ahu* construction activities, we implement Dye's (2016) 'tempo plot' procedure as a means for examining the temporal patterns of *ahu* construction events. Tempo plots utilize the raw output of OxCal's Markov-Chain-Monte Carlo (MCMC) procedure (using the *MCMC_Sample* query) to summarize the joint posteriors of multiple estimated events and to visualize the Bayes estimate and credible interval of the cumulative temporal distribution of the specified events (Dye, 2016, p. 2). Thus, the tempo plot is a summary of "how many events took place before each date in a specified range of dates" (Dye, 2016, p. 2), where the slope of the curve relates to the rate at which events occur: steeper and flatter shapes of the curve indicate more rapid or slower frequency of events, respectively. In our tempo plot, we treat the timing of initial platform construction and construction of later *ahu* components, such as plazas, ramps, and wings, as a single class of events related to *ahu* construction activities. These events encompass both initial *ahu* construction and further investments made through subsequent additions and modifications to these monuments overtime. In OxCal terms, these are the *Boundaries* for initial platform construction and start and end of TAQ phases. We also use the 'TempoActivityPlot' function of the ArchaeoPhases package (Philippe et al., 2019) to examine the patterns of *ahu* construction activity. The tempo-activity plot is similar to the normal tempo plot, but instead of plotting the cumulative number of events, it graphically displays the first derivative of the tempo plot curve. As such, the tempo activity plot shows the changing rate of construction events. The results of both analyses provide a model-based depiction of the patterns in *ahu* construction activity over time.

The later estimates in the tempo plot may be sensitive to the choice of a calendar date cutoff after which we assume no platform *ahu* were built (e.g., McCoy et al., 2012). To examine the influence of our preferred calendar date range of AD 1838–1868 on the results, we also run the tempo and tempo-activity plots with a cutoff of AD 1771 to examine whether there is a notable change in construction associated with the profound impacts of European contact (see Supplementary Materials

sections 3 and 4 for rationale).

3.6. Sample selection

In these *ahu* models, we exclude ^{14}C samples from bulk soil, those with unclear stratigraphic relationships with *ahu* features, those from the Gakushuin lab (GaK) (e.g., Ayres, 1971; Esen-Baur, 1983) known to be problematic (Blakeslee, 1994; Spriggs, 1989; Spriggs and Anderson, 1993) and samples with unknown relations between the target and dated events. For example, we exclude a number of ^{14}C determinations on abraded coral artifacts from Ahu Nau Nau at Anakena given the unknown time lag between coral harvesting and deposition at the *ahu* (Beck et al., 2003, p. 100). We also exclude obsidian hydration dates given long-standing, unresolved issues with the method (see Supplementary Materials, Section 5, Table S3). Given the general lack of short-lived samples from *ahu* contexts, we must rely on unidentified charcoal samples, which may have inbuilt age (Allen and Huebert, 2014). We apply a *Charcoal Outlier* parameter to these unidentified charcoal samples whereby all samples have a 100% probability of being outliers, which can help produce more accurate results in simulated and real-world case studies, especially when paired with multiple *Phases* (Bronk Ramsey, 2009; Dee and Bronk Ramsey, 2014). We also apply a *General* "t" type *Outlier* parameter to all identified charcoal samples to statistically assess potential poor fit between the model and radiocarbon determinations, using an outlier probability = 0.05 (Bronk Ramsey, 2009). With these uncertainties and potential issues in mind, the majority of our models for *ahu* construction are best described as TPQs for initial construction.

We present modeled results as 95.4% highest posterior density (HPD) estimates in calibrated years AD. Estimates are rounded out to nearest 5 years. ^{14}C samples used in the colonization models are included in Table S1 and samples for the *ahu* models are in Table S2. We created tempo plots in R (R Core Team, 2019) using the ArchaeoPhases package (Philippe et al., 2019). Full descriptions for each model and tempo plot, including calibration procedures, contextual information, OxCal and R code necessary for reproducing this analysis are available in Supplementary Materials.

4. Results

4.1. Rapa Nui colonization

The single-phase colonization model using only short-lived samples estimates initial colonization of Rapa Nui in the range *1150-1290 cal. AD* (A_{model} = 105.6, $A_{overall}$ = 101). Our second model that incorporates unidentified charcoal samples and a *Charcoal Outlier* parameter suggests a slightly more precise colonization estimate of *1150-1280 cal. AD* (A_{model} = 121, $A_{overall}$ = 120.5). Given the negligible difference between these two results, we opted for the more precise estimate with higher agreement indices provided by the outlier model for use in the *ahu* models and tempo plots.

4.2. Ahu construction estimates

Based on the available data, we were able to create Bayesian models for 11 *ahu*. Results for the time lag following colonization until the estimated timing of initial *ahu* construction are presented in Table 1. Fig. 3 shows the modeled distributions for these estimates. Full discussion of ^{14}C samples from *ahu* contexts and Bayesian models is provided in Supplementary Materials.

Samples within the models for *ahu* Rongo 1, Motu Toremo Hiva, Ra'ai, Ature Huki, Akivi, Vai Teka, and Tautira are comprised of unidentified charcoal, and as such these estimates may be affected by inbuilt age. Models for Ahu Heki'i, Nau Nau, and Te Niu contain both short-lived and unidentified charcoal samples in their TPQ (pre-platform) and TAQ (post-platform) *Phases* and thus their results are more accurate estimates for the timing of platform construction.

Table 1
Initial *ahu* construction. Estimates for initial platform construction for 11 *ahu* sites found across Rapa Nui and the estimated time lag between initial human colonization and construction of each *ahu*. All models have agreement indices >60. Full results and code are in Supplementary Materials.

Ahu name	Initial platform construction estimate (95.4% HPD)	Years after colonization (95.4% HPD)	A_{model}	$A_{overall}$
Akivi	*1420-1730 cal. AD*	180–515	104.8	104.3
Ature Huki	*1320-1695 cal. AD*	80–480	92.2	94.2
Heki'i	*1320-1445 cal. AD*	70–260	106.8	109.3
Motu Toremo Hiva	*1315-1415 cal. AD*	60–230	95.1	95.8
Nau Nau	*1410-1450 cal. AD*	145–285	100.2	98.1
Nau Nau IV	*1435-1655 cal. AD*	180–445	100.2	98.1
Ra'ai	*1310-1510 cal. AD*	65–310	89.2	89.1
Rongo 1	*1305-1490 cal. AD*	55–285	106.5	105.5
Tautira	*1505-1825 cal. AD*	260–610	99.7	100.2
Te Niu	*1415-1615 cal. AD*	165–405	100.8	93.6
Vai Teka	*1460-1750 cal. AD*	220–535	103.8	103.9

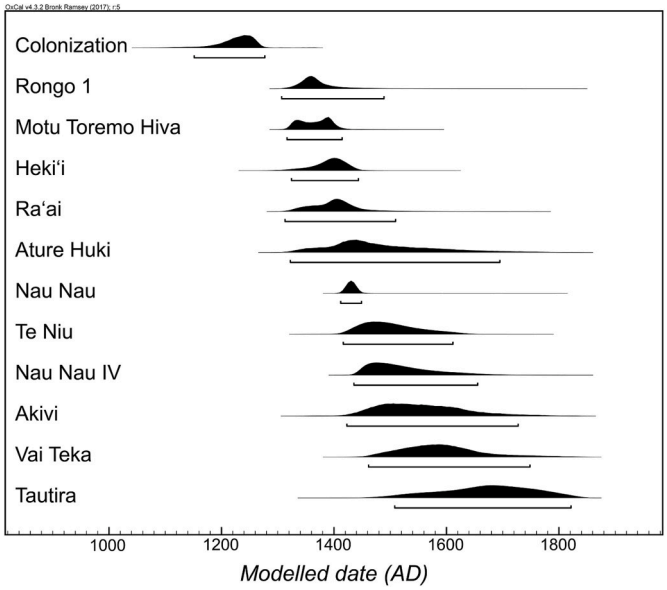

Fig. 3. Rapa Nui colonization and *ahu* construction estimates. Bayesian estimates for colonization and initial platform construction for 11 *ahu*.

4.3. Tempo of ahu construction activities

Tempo and tempo-activity plot results are shown in Figs. 4 and 5. The 11 *ahu* in our study have multiple construction elements (see Supplemental Materials), and these plots include estimated boundaries for initial platform construction, boundaries for the start of later construction episodes (TAQ *Phases*), and boundary end estimates for non-platform components. Results of the sensitivity analysis examining the effect of different calendar date cutoffs for the likely end of *ahu* construction can be found in Section 4 and Figs. S14–S17 of Supplementary Materials. For our sample of 11 *ahu*, the shape of the tempo plots using an AD 1838–1868 cutoff point indicate a fairly rapid period of *ahu* construction from ca. AD 1350–1450, followed by a steady tempo of *ahu* construction that continues beyond European contact in AD 1722. The results indicate that *ahu* construction activities continue into post-contact times, with a flattening of the upper bound of 95% credible interval at ca. 1750. The shape of tempo activity plot in Fig. 5 suggests that the rate of activity begins to slowly decline beginning around AD

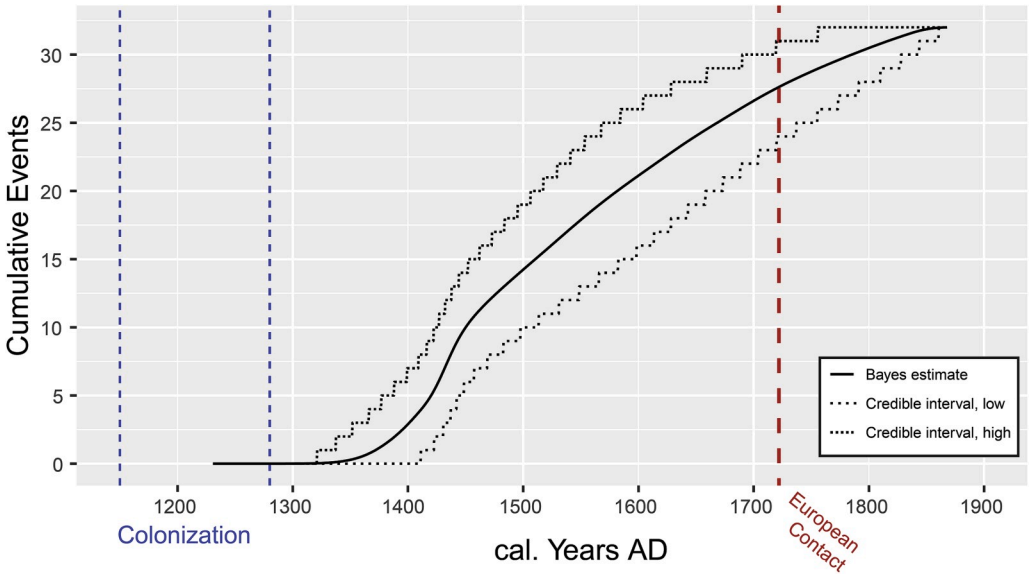

Fig. 4. Tempo of *ahu* construction events. Tempo plot for the cumulative number of *ahu* construction events, including initial construction and later building activities. Dashed lines are the upper and lower bounds of the 95% Bayesian credible intervals.

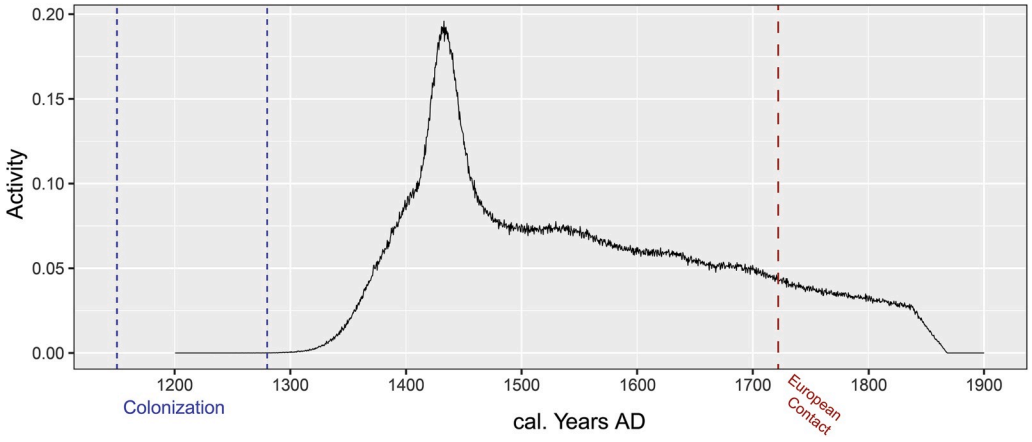

Fig. 5. Rate of change in *ahu* construction events. Tempo-activity plot showing the first derivative of the tempo plot Bayesian estimate, or rate of change over time in *ahu* construction events.

1550 through the 18th century.

Using an AD 1771 cutoff produces results that are essentially identical for time periods before AD 1700, but suggests a possible cessation of construction activities around the time of initial European contact in AD 1722 (based on the flattening of the upper bound of the 95% credible interval envelope, Fig. S15). The greatest difference between the results using the different cutoff dates is shown in the tempo-activity plots in the latter part of the 18th century (Figs. S16 and S17). Using an AD 1838–1868 cutoff suggests possible construction activities continuing just prior to this date, whereas the AD 1771 cutoff appears to artificially truncate the activity. Based on the available historical evidence and the results presented here, we suggest that ca. AD 1838–1868 is a more reasonable and conservative cutoff point. However, both iterations of the tempo plots suggest that *ahu* construction activities likely continued at least until European contact in AD 1722.

5. Discussion

5.1. Colonization estimates

Our Bayesian colonization estimate of *1150-1280 cal. AD* is in broad agreement with previous estimates based on short-lived samples (Hunt and Lipo, 2006; Lipo and Hunt, 2016; Wilmshurst et al., 2011). However, our estimate is both broader and potentially earlier than the estimate of 1200–1253 cal. AD presented in Wilmshurst et al. (2011) and Schmid et al.'s (2018) Bayesian estimate of *1245-1280 cal. AD* (*68.2% HPD*). The difference between our results and those recently published by Schmid et al. (2018) is potentially explained by their use of several younger ^{14}C samples that are unrelated to colonization, some samples not derived from archaeological contexts (e.g., those samples from Mann et al. (2008)), and their presentation of 68.2% HPD rather than 95.4% estimates. Given the available radiocarbon data, our results provide currently the most accurate, if somewhat less precise, colonization estimate for the island and add to a growing corpus of analyses suggesting initial Polynesian colonization of Rapa Nui between the late 12th and early 13th centuries AD.

5.2. The onset, tempo, and end of ahu construction activities

Our earliest estimate comes from *ahu* Rongo 1, which has an initial construction estimate of *1305-1490 cal. AD*, estimated at some 55–285 years after colonization. The latest initial construction estimate is from

ahu Tautira, estimated at *1505–1825 cal. AD*, some 260–610 years after colonization. Each of these estimates, however, are derived from unidentified charcoal samples with potential inbuilt age, and as such should be treated as TPQs for initial construction. The most secure estimates come from *ahu* Nau Nau (*1410–1450 cal. AD,* 145–285 years after colonization), Heki'i (*1320–1445 cal. AD,* 70–260 years after colonization), and Te Niu (*1415–1615 cal. AD,* 165–405 years after colonization). Hence, given the models and available data from 11 *ahu*, what we can confidently state is that initial platform *ahu* construction began sometime between the early-14th and mid-15th centuries AD. These model-based estimates for initial *ahu* construction are later than previous *ad hoc* interpretations of ^{14}C samples (Martinsson-Wallin et al., 2013; Wallin et al., 2010, p. 43; Wallin and Martinsson-Wallin, 2008, p. 154), which suggested initial construction potentially as early as 1100–1250 AD. These results have implications for monumentality in the wider region, as they call for a reassessment of previous claims that megalithic construction began on Rapa Nui prior to elsewhere in East Polynesia (Martinsson-Wallin et al., 2013). Specifically, our revised estimates for initial *ahu* construction may be penecontemporaneous with temple (*marae*) construction in central East Polynesia.

While our results are based on 11 of ca. 150 known platform *ahu* on Rapa Nui, this represents the largest possible sample of features with reliable chronological data and thus our results provide the most complete island-wide synthesis currently possible. It is possible, however, that initial *ahu* construction began earlier at locations not covered by our sample. In addition, the tempo-activity plot in Fig. 5 suggests a relatively slow decrease in the rate of *ahu* construction events from ca. AD 1550 through the 18th century, though we stress that this result should serve as a hypothesis in need of further testing as additional radiocarbon dates from *ahu* contexts become available. In particular, our analysis lacks samples from Rapa Nui's south coast, which contains some of the highest densities of large platform *ahu* on the island (Martinsson-Wallin, 1994). *Ahu* on Rapa Nui's south coast have been intensively studied by Stevenson (1986), whose work yielded a large corpus of obsidian hydration dates. Given uncertainties with obsidian hydration dating on Rapa Nui and elsewhere (see section 4 in Supplementary Materials), these dates could not be included in our Bayesian models. While Stevenson's (1986) original obsidian hydration chronology for south coast *ahu* is consistent with the results of our Bayesian models, Stevenson's (1997) later efforts that include a revised hydration rate are incompatible with both our estimate for initial colonization of Rapa Nui and the timing of *ahu* construction. This inconsistency is due to the lack of a secure clock mechanism for obsidian hydration dating (Anovitz et al., 1999), and for this reason we exclude these dates.

The most significant results from our Bayesian analyses are the tempo plots for the duration of *ahu* construction activities (Figs. 4 and 5), which provide important falsifying evidence that directly challenges core components of Rapa Nui's collapse narrative. Previous chronologies for platform *ahu* have hypothesized that their construction ceased in the 17th century (e.g., Martinsson-Wallin et al., 2013; Stevenson, 1997; Wallin and Martinsson-Wallin, 2008). The claim of a pre-contact end to platform *ahu* construction stems from assumptions about a transition in Rapa Nui culture history from an "Ahu Moai" phase, during which platform *ahu* were constructed and *moai* statues erected upon them, to a period of cultural and demographic collapse termed the "Huri Moai" phase that saw the toppling of *moai* and destruction of platform *ahu* (Kirch, 2017, 1984; Martinsson-Wallin et al., 2013). The occurrence and chronology of the Huri Moai phase are largelyconstruction activities based upon Englert's (1948) conjecture of AD 1680 as the timing for the outbreak of a war described in oral traditions collected in the late 19th and early 20th centuries; however, archaeological evidence in support of this event is either lacking or has been debunked (Lipo and Hunt, 2009; Mulrooney et al., 2009). The results of our Bayesian chronology add to these previous studies questioning the empirical sufficiency of the 'Huri Moai' phase or a cultural collapse in late pre-contact Rapa Nui. Our results also question recent claims by Rull (2016) and colleagues (Rull et al., 2018) that a major drought ca. AD 1600 caused an end to *moai/ahu* construction The results of our tempo plots indicate a rapid period of *ahu* construction between ca. AD 1350–1450 with a steady period of construction events that continue into the early historic era. In this regard, given that many of the ^{14}C dates from our sample of 11 *ahu* are from unidentified charcoal only strengthen this result, as their potential for inbuilt age may indicate that these activities occurred even more recently.

These results suggest that the activities of the so-called "Ahu Moai" phase that included statue platform construction and use likely continued up to and beyond European contact. This conclusion is bolstered by the fact that in AD 1722 the Dutch captain Jacob Roggeveen observed rituals being performed by islanders in front of statue platforms, and in 1770 the Spanish also observed that statue platforms were still being used for ritual activity (Corney et al., 1967). For example, Roggeveen (Corney et al., 1967, p. 15) states "what the form of worship of these people comprises we were not able to gather any full knowledge of, owing to the shortness of our stay among them; we noticed only that they kindle fire in front of certain remarkably tall stone figures they set up; and, thereafter squatting on their heels with heads bowed down, they bring the palms of their hands together and alternately raise and lower them." As others have argued (Boersema, 2015; Mulrooney et al., 2010), this direct observation suggests that platform *ahu* were still the focus of ritual activity at the point of, and following, European contact. This conclusion suggests that the observations made by the Dutch in AD 1722, and likely the Spanish in AD 1770, were relatively accurate depictions of Rapa Nui communities and their traditions. These findings are significant as they highlight the resilience of Rapa Nui communities following the devastating demographic impacts following European arrival (e.g., Fischer, 2005; Hunt and Lipo, 2011; Peiser, 2005; Rainbird, 2002). Indeed, the steady continuous nature of construction of *ahu* features in the history of Rapa Nui strongly supports an emerging model in which this group-level activity served as a vital component of communities necessary for long term sustainability on this tiny and remote island (DiNapoli et al., 2019, 2018; Hunt and Lipo, 2018, 2011).

6. Conclusion

In 1979, Carl Sagan popularized the aphorism "extraordinary claims require extraordinary evidence." This aphorism has become "a fundamental principle of scientific skepticism" (Voss et al., 2014, p. 893). Dramatic claims about societal collapse events require methods that are capable of linking expectations about collapse to the archaeological record. Our approach, and that of Dye (2016, 2012, 2010) offers one means of addressing this need. Here, we have provided a template for model-based approaches that address questions related to the tempo of collapse in other regions. In particular, our results highlight the utility of the tempo plot technique for quantifying the timing and rate of change in archaeological events within a Bayesian framework. To date, there have been few applications of the method beyond Dye's (2016) original formulation, which include Banks et al.'s (2019) study of the tempo of change in Upper Paleolithic lithic typologies and Marsh et al.'s (2017) examination of the expansion of the Inca Empire. Our results demonstrate that the tempo plot technique has wide applicability for quantifying the timing and rate of change of archaeological processes, in particular declines or cessation of activities associated with purported 'collapse' events and provides a viable alternative to the more common approach of using summed probability distributions of radiocarbon dates. Tempo plots can also provide a useful extension of more common Bayesian approaches and offer ways to better characterize and quantify similar case studies around the world, such as the rate of decline at various Maya political centers (e.g., Ebert et al., 2017, 2016; Hoggarth et al., 2016) and other areas (e.g., Bar-Oz et al., 2019; Carter et al., 2019; O'Shea et al., 2019).

Rapa Nui remains one of the most popular accounts of a society that

self-destructed and is persistently used as a paragon of societal collapse. In particular, there are numerous recent non-archaeological studies that treat this collapse event as fact, and which attempt to use Rapa Nui to validate and calibrate general-purpose economic and demographic models (e.g., Akhavan and Yorke, 2019; Anderies, 2000; Basener and Ross, 2004; Basener and Basener, 2019; Bologna and Flores, 2008; Brander and Taylor, 1998; Brandt and Merico, 2015; Cazalis et al., 2018; D'Alessandro, 2007; Dalton et al., 2005; Dalton and Coats, 2000; de la Croix and Dottori, 2008; Dockstader et al., 2019; Erickson and Gowdy, 2000; Pezzey and Anderies, 2003; Reuveny, 2012; Reuveny and Decker, 2000; Roman et al., 2017; Takács et al., 2019; Uehara et al., 2010). The results of our Bayesian models, along with recent dates from the Rano Raraku statue quarry (Sherwood et al., 2019; Simpson et al., 2018), indicate there was not a pre-contact 'collapse' in *ahu* or *moai* construction, but that monument activity continued into the post-contact era. These findings add to the growing corpus of independent lines of evidence contradicting the traditional 'collapse' narrative for Rapa Nui (Hunt and Lipo, 2011; Lipo et al., 2016; Mulrooney, 2013; Mulrooney et al., 2010; Simpson and Dussubieux, 2018), and thus question the results of a broad range of interdisciplinary research on societal collapse that assume the occurrence of this event with certainty.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2020.105094.

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