ANTHROPOLOGY

Reevaluating human colonization of the Caribbean using chronometric hygiene and Bayesian modeling

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Human settlement of the Caribbean represents the only example in the Americas of peoples colonizing islands that were not visible from surrounding mainland areas or other islands. Unfortunately, many interpretive models have relied on radiocarbon determinations that do not meet standard criteria for reporting because they lack critical information or sufficient provenience, often leading to specious interpretations. We have collated 2484 radiocarbon determinations, assigned them to classes based on chronometric hygiene criteria, and constructed Bayesian colonization models of the acceptable determinations to examine patterns of initial settlement. Colonization estimates for 26 islands indicate that (i) the region was settled in two major population dispersals that likely originated from South America; (ii) colonists reached islands in the northern Antilles before the southern islands; and (iii) the results support the southward route hypothesis and refute the "stepping-stone model."

INTRODUCTION

Radiocarbon (^{14}C) dating is the most frequently used chronometric technique in archaeology given its wide applicability and temporal range that covers the last ca. 50 ka. Preserved carbon-based organic materials such as charcoal, shell, and bone are often key sources of information for determining the onset and duration of cultural events that occurred in the past. Unfortunately, building refined chronologies in many regions has been hampered by a lack of critical evaluation and application of radiocarbon dating. The Caribbean is no exception in this regard.

Initial human colonization of the insular Caribbean, which comprises more than 2.75 million km^2 of open water, represents one of the most remarkable, but least understood population dispersals in the human history. In archaeology, the term "colonization" as it applies to initial human settlement of a landscape has not always been readily defined. For the purposes of this paper, we follow other case studies that define colonization as the earliest reliable (i.e., unambiguous) evidence for human arrival to previously uninhabited landmasses [e.g., (*1*)]. What sets the Caribbean apart from the rest of the Americas is that these colonization events are the only instances where ancient Amerindian groups would have crossed hundreds or even thousands of kilometers of open sea using watercraft—likely single-hulled canoes—to reach uninhabited islands after losing sight of land, either from surrounding mainland areas or between the islands themselves (*2*). However, the onset, tempo, and origin of these movements are still debated (*3*, *4*), and persistent problems with how radiocarbon determinations are used and reported have plagued Caribbean archaeology. Many published determinations lack the necessary information essential to adequately examine potential sources of error (e.g., contamination, poor cultural associations, taphonomic issues, or publication of uncorrected marine determinations), all of which can greatly influence archaeological interpretation (*5*–*7*).

This lack of rigor in reporting radiocarbon determinations brings into question the temporal efficacy of the region's cultural-historical framework for various phases of settlement and subsequent cultural behaviors. One major outcome has been an ongoing debate regarding how, when, and from where the Caribbean islands were first colonized during both the Archaic ca. 7000–2500 B.P.) and Ceramic Ages (beginning ca. 2500 B.P.), during which groups are thought to have ventured north from somewhere along the South American mainland. This is highlighted in two competing models: (i) the "stepping-stone" model, which suggests a general south-to-north settlement from South America through the Lesser Antilles into the Greater Antilles (*8*), and (ii) the "southward route hypothesis", which proposes that the northern Antilles were settled directly from South America followed by progressively southward movement(s) into the Lesser Antilles (Fig. 1) (*9*).

Like other world regions where humans appear to have moved rapidly through landscapes or seascapes, such as the Pacific colonization of Remote Oceania that took place in stages from different points of origin—or in North America where the coastal migration versus the ice-free corridor debate has raged for decades—support for one model or another largely depends on the number, quality, and suitability of radiocarbon determinations used in analysis. For the Caribbean, this not only has relevance for establishing the routes of dispersal but also has important implications for understanding other natural and social variables that would have influenced the movement of peoples in watercraft that possibly encouraged (or discouraged) travel, including prevailing oceanographic conditions (e.g., currents, winds), climatic anomalies (e.g., El Niño), technological capabilities, or natural events (e.g., volcanism) (*2*, *3*).

A common approach to improving the efficacy of large radiocarbon inventories in the event of unreliable or inadequately reported determinations is to apply a chronometric hygiene protocol [e.g., (*5*, *10*, *11*); see Materials and Methods]. In this selection process, determinations are assigned to different reliability classes that effectively cull spurious radiocarbon determinations. To resolve many of the issues related to our understanding of the timing and trajectories of Caribbean colonization, we have compiled the largest publicly available database of radiocarbon determinations for the region (n = 2484), applied a chronometric hygiene protocol, and found that

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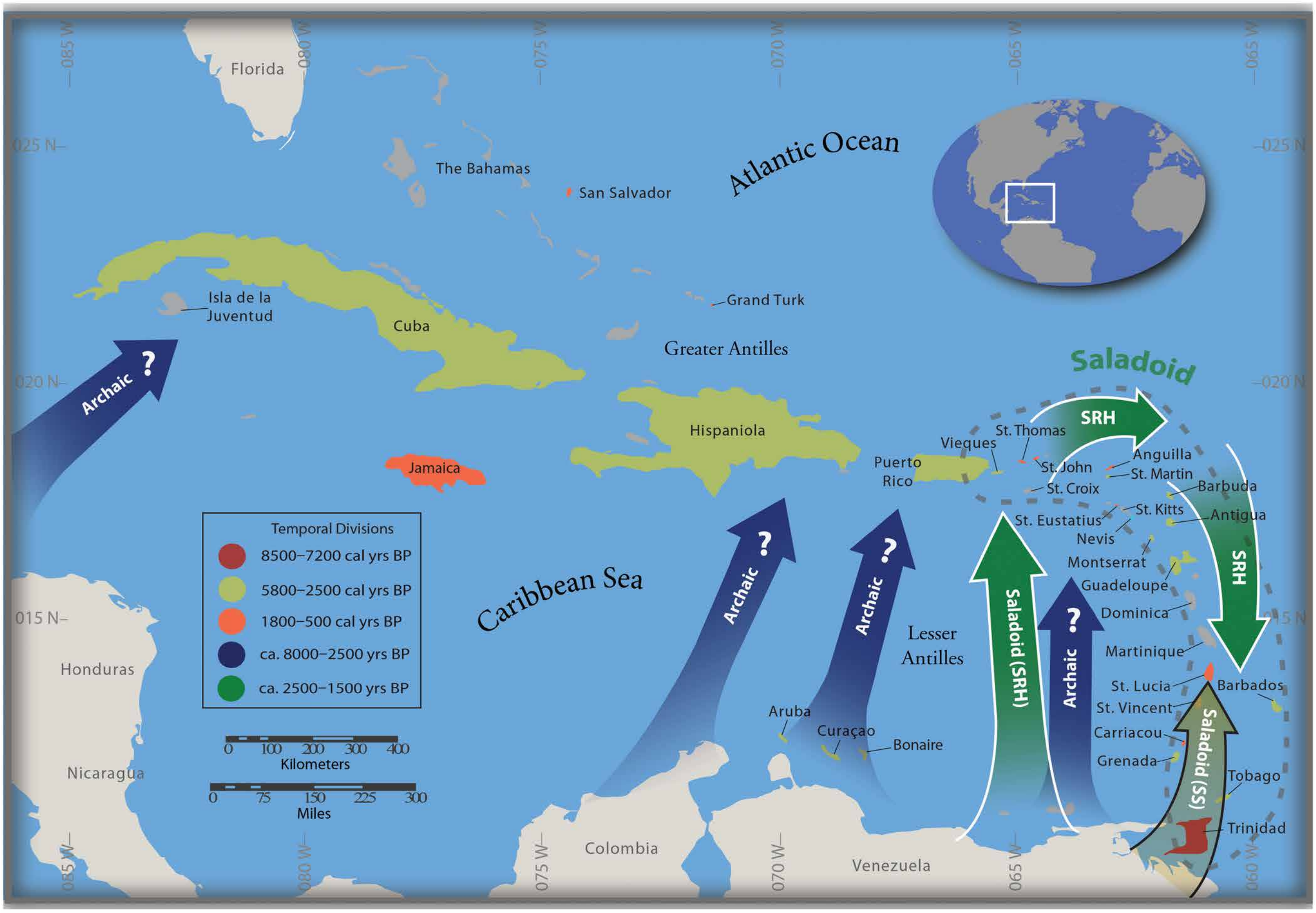

Fig. 1. Bayesian modeled colonization estimates for 26 Caribbean islands suggest two distinct population dispersals. Colonists reached islands in the northern Antilles bypassing islands in the southern Lesser Antilles, refuting a stepping stone pattern. SS denotes the stepping stone model, and SRH denotes the southward route hypothesis.

only 54% of dates meet current reporting standards. Radiocarbon determinations from 55 islands were obtained through an extensive literature review, including available English, Spanish, and French publications, and were bolstered by contacting more than 100 researchers and radiocarbon laboratories to obtain unpublished or underreported determinations and their associated data. These efforts have more than tripled the number of radiocarbon dates used in the last assessment (*5*). Bayesian analyses of the resulting acceptable 1348 determinations for 26 Caribbean islands provide the first model-based age estimates for initial human arrival in the Caribbean and help resolve long-standing debates about initial settlement of the region.

Following results of the first chronometric hygiene study done for the Caribbean more than a decade ago (*5*), we expect that many islands will have younger colonization estimates after the hygiene protocol is applied, a result also seen in other similar studies (*11*). Hence, we examine competing colonization models using only the most reliable determinations from this enhanced database.

Background

For decades, archaeologists have assumed that the Caribbean was settled in multiple stages and directions. The first, termed "Lithic" (*8*, *12*, *13*), was said to originate in Mesoamerica with dispersal into Cuba and through parts of the Greater Antilles ca. 6000–5000 cal years B.P. The evidence for this is based almost solely on the perceived similarity in stone tools, ephemeral archaeological assemblages, and a limited number of radiocarbon dates (*3*, *13*). The second was a northward movement from South America around the same time or slightly earlier known as the "Archaic." While both the Lithic and Archaic Ages are now generally referred to as the Archaic regardless of supposed origin, it is evident that not all islands in the Antilles were settled during this time for reasons that are still unclear (*3*). It was not until thousands of years later, ca. 2500 B.P., that an apparently new migratory group known as Saladoid—named after the Saladero site in Venezuela where distinctive pottery was first identified—moved into Puerto Rico and much of the Lesser Antilles. However, Saladoid dates are not all contemporaneous, and some islands remained uninhabited until much later.

Apart from Trinidad, which today is only 10 km from Venezuela and was connected to the mainland by a land bridge during the Late Pleistocene/Early Holocene (*14*), it was recognized that the oldest radiocarbon dates in the region—both for initial colonization (Lithic/Archaic) and later Saladoid populations—were found in the northern Caribbean (e.g., Cuba, Puerto Rico, St. Martin, and Anguilla). Yet, there had been no substantive attempt to compile or critically examine larger datasets to investigate this model in more detail until Fitzpatrick's study in 2006.

The long-held stepping-stone model in which groups originating in South America moved northward through the Lesser Antilles and Puerto Rico, and then eventually west into the rest of the Greater Antilles, does not discount a possible earlier migration eastward from Mesoamerica into Cuba [e.g., (*8*)]. In this model, groups were able to move quickly through the Lesser Antilles because of the close proximity and intervisibility of islands once peoples reached Grenada. Chronological support for this model would require that the oldest radiocarbon dates be found in the southern Lesser Antilles with those in Puerto Rico occurring later in time (presuming a slight lag as movement progressed northward), or at the very least, contemporaneous if movement was rapid (*9*). This has been the prevailing model for decades, in part because of the ubiquity of Saladoid pottery found throughout Puerto Rico and the Lesser Antilles and the assumption that their presence was coeval. Despite some scholars noting a discrepancy in which dates in the northern Antilles were older than those in the south, the SS model had not been explicitly tested, despite evidence that pottery styles were not always reliable chronological markers (*7*, *9*).

The prevailing stepping-stone model was challenged more than two decades ago when computer simulations of seafaring suggested that migrants voyaging from South America would have had the highest probability of initial landfall in the northern Caribbean due to the consistently strong easterly trade winds blowing through the southern Lesser Antilles and ocean currents that flow in the same direction, making eastward progress difficult, if not impossible (*15*). Fitzpatrick (*5*) was the first to examine this problem using quantitative archaeological data. After reviewing more than 600 radiocarbon dates from 36 Caribbean islands, he came to a similar conclusion, showing that the earliest acceptable dates for Saladoid—as well as earlier Archaic settlement—were found in the northern islands, with first settlement of the southern Lesser Antilles, Bahamas, and Jamaica occurring centuries later after a “long pause” of around 1000 years (*5*).

As a result of these studies, a second model, termed the southward route hypothesis, suggested that there was instead a direct movement from South America to the northern Caribbean (Puerto Rico and the northern Lesser Antilles) that initially bypassed the southern Lesser Antilles [see (*2*, *5*, *9*, *13*)]. This model largely rejects a Mesoamerican origin based on spurious data and assumes that the oldest radiocarbon dates are found in the northern Lesser Antilles and Puerto Rico based on previous chronometric hygiene analysis (*5*). Giovas and Fitzpatrick (*16*) further explored this scenario using an ideal free distribution framework. Their results indicated that settlement location was likely influenced by the attractiveness of resources, available land, and seafaring limitations. Together, these factors suggested that dispersals were fluctuating and opportunistic, leading to settlement of the largest and most productive islands first, followed by a gradual southward movement ca. 2000 cal years B.P. Only around 500 years later ca. 1400 cal years B.P. were Jamaica and the Bahamas occupied for the first time (Fig. 1).

More recently, analyses of paleoenvironmental data from lake cores showing an increase in charcoal particle concentrations and changes in vegetation regimes through time have also recently been used as proxy evidence in support of an even earlier settlement of many islands, in some cases thousands of years before the archaeological evidence (*17*–*19*). However, we do not view the results of these paleoenvironmental surveys as convincing evidence of human colonization as the data used in these analyses are often not clearly from cultural contexts nor do they contain unequivocal anthropogenic signatures such as pollen or other micro- or macrobotanical remains from introduced cultigens [see also (*20*–*22*)]. Nonetheless, the argument has revitalized the notion of a northward stepping stone population movement, one that is much earlier than archaeological records indicate.

Fitzpatrick’s previous chronometric hygiene study more than 10 years ago revealed that 87.6% of the radiocarbon dates available at that time were acceptable (*5*). In addition, only 21 (58.3%) of 36 islands examined had any archaeological sites with at least three radiocarbon dates; astonishingly, 127 (73.8%) of 172 sites in the dataset had three or fewer dates. While this earlier study was relatively thorough, there were still an unknown number of dates unavailable due to issues of accessibility (e.g., contract-based gray literature) or nonreporting. Fortunately, there has been a considerable increase in published radiocarbon dates over the past decade that has substantially expanded the amount of chronological data available. The greater number of radiocarbon dates for the Caribbean now has the potential to dramatically improve our understanding of the mode and tempo of prehistoric colonization and a host of other issues, such as measuring human impacts on island ecosystems and reconstructing paleoecological and paleoclimatological conditions through time. However, many of the same problems with radiocarbon dating that were prevalent 13 years ago persist today, including the use of unidentified wood from potentially long-lived taxa, unknown marine reservoir corrections, and/or the inclusion of dates from contexts that are not clearly anthropogenic. Because all of these issues require chronometric hygiene before colonization models can be sufficiently reevaluated, the data presented here comprise the largest compendium of radiocarbon determinations yet assembled for the Caribbean, which are used to create the first model-based colonization estimates for 26 islands.

RESULTS

A total of 2484 radiocarbon determinations were compiled from 585 sites on 55 islands (table S1). Dates were assigned to one of four classes using chronometric hygiene protocols (see Materials and Methods for criteria). Only 10 dates (0.40%) met criteria for Class 1 (most acceptable dates), and 1338 (53.9%) dates met the criteria for Class 2, for a total of 1348 (54.3%) dates that were considered acceptable for Bayesian analysis (see Methods and Materials for a description of class criteria). Seventeen islands (31.0%) with radiocarbon dates did not have any Class 1 or 2 dates (Table 1). Despite a tremendous increase in research and publication over the past decade, 433 (74.0%) archaeological sites still have three or fewer radiocarbon determinations, and 237 (40.5%) sites only have a single date representing an entire site. This is a minimal change compared with the earlier study a decade ago where 164 (39.4%) sites had a single reported radiocarbon date (*5*). Surprisingly, only 881 published radiocarbon determinations (35.5%) contained $^{13}C/^{12}C$ values ($\delta^{13}C‰$), many of which were only made available after contacting the author or radiocarbon laboratory. These values are important for understanding whether dates were corrected with estimated values, the $\delta^{13}C‰$ in the sample itself, and whether the fractionation was calculated using accelerator mass spectrometry (AMS) or isotope ratio mass spectrometry (IRMS).

Consequently, many islands settled before European contact were excluded from our Bayesian modeling, which only used Classes 1

Table 1. Results of chronometric hygiene by island.

	Abaco	Andros	Anegada	Anguilla	Antigua	Aruba	Baliceaux
Class 1	—	—	—	—	—	—	—
Class 2	1	—	—	41	18	25	2
Class 3	5	2	1	10	51	19	1
Class 4	—	—	—	—	10	6	—
Total	6	2	1	51	79	50	3

	Barbados	Barbuda	Bonaire	Carriacou	Cayman Brac	Crooked Island	Cuba
Class 1	—	—	—	—	—	—	—
Class 2	9	19	16	45	—	4	169
Class 3	13	24	8	1	2	7	31
Class 4	8	6	1	1	8	1	6
Total	30	49	25	47	10	12	206

	Curaçao	Dominica	Eleuthera	Grand Turk	Great Camanoe	Grenada	Guadeloupe
Class 1	—	—	—	3	—	—	—
Class 2	26	5	1	14	—	27	23
Class 3	54	2	4	8	—	8	24
Class 4	6	1	11	1	1	22	16
Total	86	8	16	26	1	57	63

	Guana Island	Hispaniola	Inagua	Isle de la Gonâve	Jamaica	Jost Van Dyke	Long Island
Class 1	—	1	—	—	—	—	—
Class 2	—	43	—	—	10	2	—
Class 3	—	99	5	2	36	—	—
Class 4	1	83	—	—	32	—	7
Total	1	226	5	2	78	2	7

	Los Roques	Marie-Galante	Martinique	Middle Caicos	Mona Island	Montserrat	Mustique
Class 1	—	—	—	—	2	—	—
Class 2	1	—	5	—	2	15	3
Class 3	—	—	5	7	4	5	6
Class 4	3	2	14	1	—	11	—
Total	4	2	24	8	8	31	9

	Nevis	Pine Cay	Providenciales	Puerto Rico	Saba	San Salvador	St. Croix
Class 1	—	—	—	4	—	—	—
Class 2	10	—	—	447	2	14	5
Class 3	12	1	8	35	37	7	1
Class 4	—	—	—	48	2	18	5
Total	22	1	8	534	41	39	11

	St. Eustatius	St. John	St. Kitts	St. Lucia	St. Martin	St. Thomas	St. Vincent
Class 1	—	—	—	—	—	—	—
Class 2	12	14	2	18	81	61	6
Class 3	6	8	—	6	42	16	3
Class 4	1	2	1	9	5	47	—
Total	19	24	3	33	128	124	9

	Tobago	Trinidad	Union Island	Vieques	Water Island	West Caicos
Class 1	—	—	—	—	—	—
Class 2	15	49	—	68	7	—

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	Tobago	Trinidad	Union Island	Vieques	Water Island	West Caicos
Class 3	10	15	1	53	—	1
Class 4	2	31	—	—	—	—
Total	27	95	1	121	7	1

and 2 dates. For example, while it is clear that Saba has a rich prehistoric record (*23*), it was not modeled due to the lack of acceptable radiocarbon determinations (two Class 2 dates out of 41 total determinations) based on our chronometric hygiene criteria. Similarly, our chronometric hygiene protocol and Bayesian analyses show that the modeled colonization estimate for Nevis is *1425–1000 cal years B.P.* [95% highest posterior density (HPD)], despite the presence of the Hichmans site, which was identified as an earlier Archaic settlement containing an assemblage similar to other Archaic sites on nearby islands (*24*, *25*). Our results suggest a more recent settlement chronology for many islands similar to other chronometric hygiene studies [e.g., (*11*)] and highlight important problems with the quality of radiocarbon dates in the region and/or misinterpretation of supposed earlier dates, as many of those previously reported fail to meet criteria for accurate, reliable reporting.

Class 1 dates include those from the Coralie site on Grand Turk (*26*), a cenote from Manantial de la Aleta on Hispaniola (*27*), Cave 18 on Mona Island (table S1), and two sites on Puerto Rico: AR-39 (*28*) and Cag-3 (*29*) (Table 2). One of three Class 1 radiocarbon determinations from the Coralie site is the oldest acceptable date from Grand Turk, but three Class 1 dates are not enough to produce a robust colonization estimate. The remaining Class 1 dates from Hispaniola, Puerto Rico, and Mona Island likely do not date to first colonization of those islands. Together, these 10 dates cannot be used to evaluate different colonization models. Therefore, we have chosen to instead generate colonization models using Class 1 dates and the larger, more robust Class 2 data set.

Of 55 islands, 26 met the criteria for Bayesian modeling. Nearly all Class 2 determinations from wood samples were from unidentified taxa or could potentially be long-lived species that can present inbuilt age problems. Therefore, modeled colonization estimates were produced using the Charcoal_Outlier analysis in OxCal, which treats radiocarbon determinations on unidentified wood as having 100% probability of having as much as 100 years of inbuilt age [(*30*, *31*); see Materials and Methods]. All islands selected for Bayesian modeling possessed nine or more acceptable dates and produced a model agreement (A_{model}) ≥77.9% and an overall agreement (A_{overall}) ≥62.8% (Table 3; see Materials and Methods).

The oldest modeled dates for Cuba (LE-4283) and Vieques (I-16153) had poor agreement indices, but the model agreement (A_{model}) and overall agreement (A_{overall}) remained high (Table 3 and tables S2 to S4). Poor agreement indices were likely caused by a gap between the oldest modeled dates and the rest of the Phase, caused by both the chronometric hygiene protocol and a relative dearth of radiocarbon determinations dating to early settlement when compared with later periods.

Bayesian modeling of Classes 1 and 2 radiocarbon dates from each island markedly truncates the earliest estimated date of human settlement for six modeled islands. The biggest differences are for Anguilla, Cuba, Hispaniola, and Puerto Rico, which are as much as ca. 2100 to 2300 years younger than previously reported. Although still dating to the Archaic Age (ca. >2500 cal years B.P.), the modeled colonization estimate places human settlement of Puerto Rico and Hispaniola after other islands such as Cuba, Curaçao, St. Martin, and, possibly, Barbados.

DISCUSSION

The results of our chronometric hygiene and Bayesian modeling both support and offer new perspectives on the pattern of pre-Columbian colonization of the Caribbean islands. Trinidad produced the oldest colonization model estimate of *8420–7285 cal years B.P.* (95% HPD). This is expected given that lower sea levels in the Late Pleistocene and Early Holocene either connected or placed Trinidad close enough to the South American mainland to allow for settlement that would not have necessarily required sophisticated (or any) watercraft (*14*). Consequently, early sites on Trinidad should be considered differently when compared with other islands in the Antilles where long-distance seafaring and more advanced wayfinding skills were likely required to colonize (*3*, *7*). After Trinidad, our results suggest two distinct clusters of colonization estimates modeled from ca. 5800–2500 cal years B.P. and 1800–500 cal years B.P. (Figs. 1 and 2).

The two clusters fit well with generally accepted cultural divisions in the Caribbean. The first cluster, ca. 5800–2500 cal years B.P., suggests two distinct population dispersals into the Caribbean that span the Archaic and the inception of the Ceramic Age. The earliest settled islands in the first cluster of our model, ca. 5800–2500 cal years B.P., are Cuba, Hispaniola, and Puerto Rico in the Greater Antilles; Gaudeloupe, St. Martin, Vieques, St. Thomas, Barbuda, Antigua, and Montserrat in the northern Lesser Antilles; Barbados and Grenada in the southern Lesser Antilles; and Aruba, Bonaire, and Curaçao, located relatively close (27, 88, and 65 km, respectively) to mainland South America, along with Tobago, which is 35 km northeast of Trinidad (Fig. 1). Before our chronometric hygiene, the oldest reported radiocarbon dates in the Greater Antilles suggested that Archaic populations reached the area as early as ca. 7400–6900 cal years B.P. (*3*, *5*). Together, these results for earliest settlement are consistent with the southward route hypothesis and suggest that some of the largest and most resource-rich islands in the northern Caribbean were settled first (*14*). In addition, our analysis places Curaçao in the earliest cluster, which may be explained by its close proximity to mainland South America. Barbados represents an exception and has long been thought to be an interesting case of anomalous early settlement of the southern Lesser Antilles; our results continue to support this notion (*3*, *32*).

These results suggest that after the initial settlement of larger islands in the Greater Antilles and some of the smaller islands close to the mainland during the Archaic period, subsequent Ceramic Age settlement focused again on additional smaller islands close to the mainland and several in the northern Lesser Antilles, including those close to

Table 2. Class 1 dates from the Caribbean. EU, excavation unit; cmbd, centimeters below datum.

Island	Site	Sample material	Sample type	Provenience	Laboratory number	Conventional radiocarbon age (B.P.)	Error	$\delta^{13}C$ (‰)	Reference
Grand Turk	Coralie Site	Charcoal: palm	Charcoal/charred material	124 N 100E FS no. 35 47-62 cmbd, Hearth Feature 5	Beta-80910	1160	60	—	Carlson 1999
Grand Turk	Coralie Site	Charcoal: wild lime	Charcoal/charred material	110 N 110E, FS no. 81, 92-93.5 cmbd, ash lens area 10	Beta-80911	1280	60	—	Carlson 1999
Grand Turk	Coralie site	Wood, cf. bullwood	Wood	Mangroves paddle, peat layer	Beta-96700	940	60	—	Carlson 1999
Hispaniola	Manantial de la Aleta	Gourd	Plant material	Cenote	Beta-107023	940	30	—	Conrad *et al.* 2001:14
Mona Island	Cave 18	*Amyris elemifera*	Charcoal/charred material	Cave 18	OxA-31209	454	23	−28.2	Samson and Cooper, personal communication
Mona Island	Cave 18	*Bursera simaruba*	Charcoal/charred material	Cave 18	OxA-31536	682	26	−26.9	Samson and Cooper, personal communication
Puerto Rico	AR-39	*Nesotrochis debooyi*	Faunal material	Feature 3 (northern area); EU 17, level 3	Beta-221018	1340	40	−21.1	Carlson and Steadman 2009
Puerto Rico	Cag-3	*Heteropsomys insulans* (mandible)	Faunal material	Grave infill	OxA-15142	1219	26	−19.6	Turvey *et al.* 2007:195
Puerto Rico	Cag-3	*Nesophontes edithae* (mandible)	Faunal material	Grave infill	OxA-15141	990	24	−19.3	Turvey *et al.* 2007:195
Puerto Rico	Cueva María de la Cruz	Sapotaceae seed	Plant material	Unit 102: 95–113 cmbd	Beta-347456	1910	30	−22.7	Oliver and Rivera Collazo 2015

islands previously settled during the Archaic. This is not entirely unexpected, for subsequent population dispersals such as Saladoid are likely to have followed similar trajectories, particularly if there had been a long tradition of ancestral groups traveling between the mainland and the Antilles over the course of centuries or even millennia.

The second cluster of colonization estimates fall between ca. 1800 and 500 cal years B.P. and corresponds to another burst of activity in which several islands in both the northern (St. John, St. Eustatius, Nevis, and Anguilla) and southern (St. Lucia and Carriacou) Lesser Antilles were colonized. Settlement of the Bahamian Archipelago also takes place within this time period on Grand Turk and San Salvador. It is possible that the chronologies reflect multiple groups moving in various directions (northern and southern) simultaneously, an expected outcome as trade and exchange relationships quickly accelerated after Saladoid occupation (*4*).

Our results place Anguilla within this later cluster, which likely reflects the results of chronometric hygiene and the removal of the oldest dates for the island given that many of these are reported without provenience and had to be excluded from analysis. The previously accepted earliest radiocarbon determinations from Anguilla were on *Lobatus* sp. shell tools from surface contexts. However, given the lack of stratigraphic control, those determinations were discarded from our analysis. This does not rule out an earlier settlement of the island, but currently well-anchored radiocarbon evidence is lacking.

The research presented here has important implications for examining previous explanatory models of human dispersal into the Caribbean. First, with the use of only the most secure radiocarbon determinations, our results do not support an initial northward stepping stone pattern, once the dominant scenario and resurrected by proponents of recently collected paleoenvironmental data (*17*). Instead, our results suggest that islands in the Greater Antilles, in the northern Lesser Antilles, and located very close to the South American mainland have the earliest reliable radiocarbon determinations and modeled chronologies. These data are consistent with the general predictions of island biogeography in which the closest and largest islands are colonized first (*33*, *34*), as well as the southward route hypothesis, whereby the largest and/or most northerly islands in the Antilles were initially colonized with subsequent settlement proceeding southward through the Lesser Antilles. These results are also supported by previous chronometric hygiene analyses (*5*), seafaring simulations (*32*), fine-grained ceramic analysis (*35*), and predictions of the ideal free distribution model (*16*).

Despite consistency with previously proposed models, there are some islands that were settled anomalously later than would be expected or not at all. For example, Jamaica has no known Archaic or

Table 3. Modeled colonization estimates using the 100-year outlier model. Puerto Rico was modeled with the 100 oldest determinations (see Materials and Methods).

Island	Total number of dates	Number of modeled dates	Results			
			68.2 (cal B.P.)	95.4 (cal B.P.)	A_{model}	$A_{overall}$
Anguilla	51	41	*1420–1260*	*1510–1180*	77.9	77.1
Antigua	79	18	*3100–2830*	*3385–2750*	103.2	102.9
Aruba	50	25	*3670–3450*	*3895–3295*	100.8	98.1
Barbados	30	9	*4985–4485*	*5885–4440*	100.2	100.1
Barbuda	49	19	*3455–3265*	*3715–3225*	99.6	99.6
Bonaire	25	16	*3715–3470*	*4060–3410*	98.1	98.0
Carriacou	47	45	*1500–1415*	*1550–1385*	81.3	62.8
Cuba	206	169	*5055–4790*	*5360–4675*	85.6	80.4
Curaçao	86	26	*5350–4970*	*5685–4845*	97.8	94.5
Grand Turk	25	17	*1300–1105*	*1435–1025*	82.6	82.4
Grenada	57	27	*2675–2495*	*2835–2430*	95.5	95.7
Guadeloupe	63	24	*3460–3135*	*3770–2635*	104.0	86.8
Hispaniola	226	44	*4385–4040*	*4545–3930*	97.4	96.0
Jamaica	78	10	*980–575*	*1015–475*	108.0	107.8
Montserrat	31	15	*3045–2780*	*3355–2590*	100.0	100.1
Nevis	22	10	*1220–1050*	*1425–1000*	101.0	101.5
Puerto Rico	518	100	*4580–4390*	*4655–4305*	116.1	105.4
San Salvador	37	14	*1115–935*	*1230–795*	88.9	89.4
St. Eustatius	19	11	*1760–1570*	*1835–1340*	100.5	100.3
St. John	24	14	*1555–1305*	*1670–1095*	100.4	98.5
St. Lucia	33	18	*790–705*	*885–685*	109.6	72.0
St. Martin	105	81	*5155–4995*	*5275–4940*	96.0	93.6
St. Thomas	116	61	*2880–2620*	*2970–2485*	119.7	96.4
Tobago	27	15	*2990–2770*	*3355–2750*	110.5	108.1
Trinidad	95	49	*8160–7900*	*8420–7285*	103.8	100.4
Vieques	121	68	*4065–3855*	*4200–3745*	91.9	93.1

Saladoid settlements, with the earliest sites containing Ostionoid ceramics (post ca. 1400 B.P.). The Cayman Islands have no evidence for settlement before European arrival, despite several attempts by researchers to locate archaeological sites (*3*, *36*). The disparity in these dates could be attributed to environmental factors, such as rough sea conditions that complicated successful navigation to these islands (*37*), survey and excavation bias, the obscuring of evidence due to natural and/or cultural processes (e.g., sea level changes, volcanism, commercial development), or other unknown reasons. This demonstrates that the investigation of when and how island regions were colonized must be treated on an island-by-island basis and not generalized across whole regions or archipelagos, as many other variables (e.g., cultural, oceanographic, and geologic) likely influenced population dispersals.

Our analysis, while using the most robust chronological dataset yet compiled for the Caribbean, is still limited by incomplete or unpublished information as well as biased survey coverage for various sites and islands. Suggested colonization estimates are presented using only the most secure chronological data available, but doing so led to the exclusion of more than 1000 radiocarbon determinations. The very nature of chronometric hygiene means that in addition to removing erroneous assays, it is likely some dates that were discarded from further analysis are in fact representative of cultural activities during that time but do not fulfill the imposed criteria (*38*, *39*). A recent discussion by Dye (*40*) suggests that these problems of chronometric hygiene and single-phase Bayesian models can potentially be resolved using two-phase models. Dye (*40*) took this approach for examining Pacific Island colonization and modeled the first phase using radiocarbon dates from precolonization paleoenvironmental data that directly preceded the first evidence for human colonization. This first phase of the model helps to establish a cutoff point for the second colonization phase of the model, which serves as a step in conjunction with chronometric hygiene in deciding what chronometric data are most reliable. While robust and reliable precolonization paleoenvironmental data are currently lacking for most Caribbean islands [cf. (*17*)], the use of two-phase Bayesian models in future studies will likely improve the accuracy and precision of our colonization estimates. Another argument is that temporally diagnostic

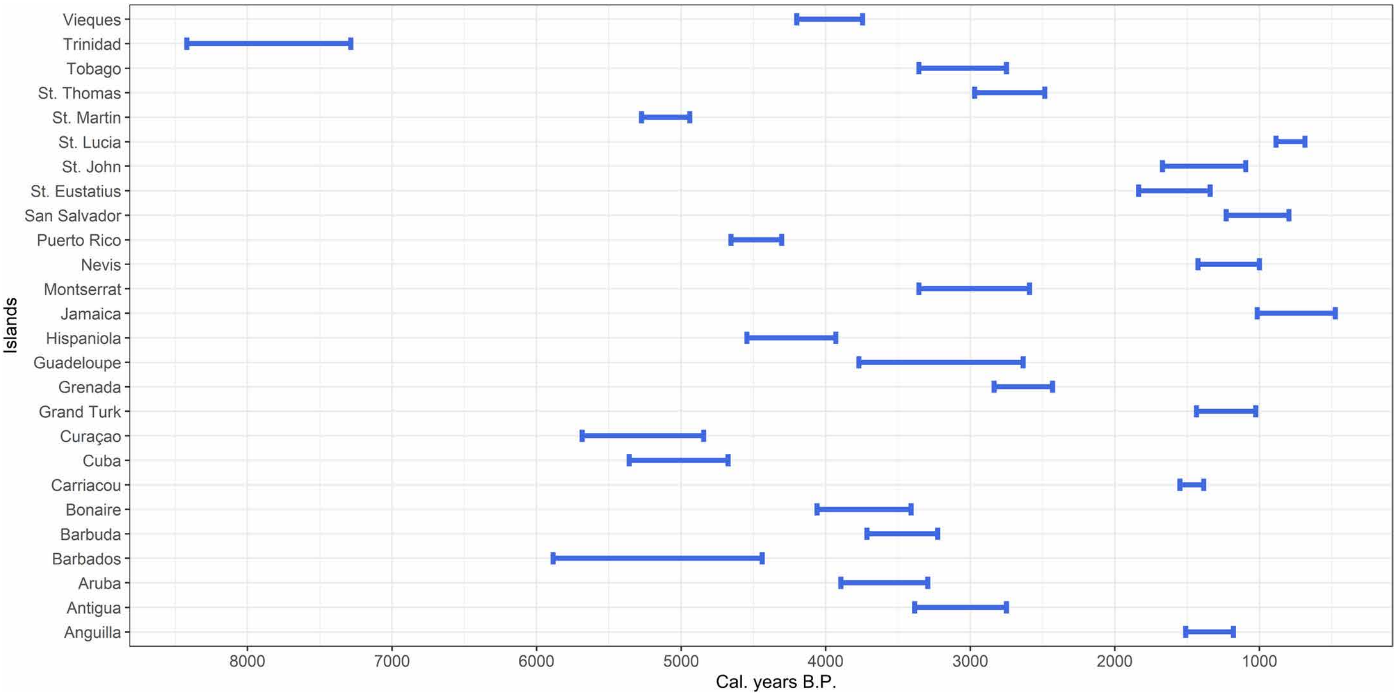

Fig. 2. Colonization age estimates (95% HPD) after chronometric hygiene and Bayesian modeling.

objects such as pottery could be used in the absence of radiocarbon determinations to potentially fill in gaps created by chronometric hygiene. However, without the inclusion of additional absolute chronometric techniques (e.g., thermoluminescence and uranium-thorium), pottery and other diagnostic artifacts such as typologically distinct lithics only serve as good chronological markers when they are first anchored by reliable absolute dates. For example, Cedrosan Saladoid pottery, thought only to occur in pre-2000 year B.P. sites, has been recovered on some islands like Carriacou, where the earliest acceptable dates are much later in time ca. *1550–1375 cal years B.P.* (95% HPD) (with only 4.3% of determinations from the island rejected). One implication of our revised colonization chronologies is that other long-accepted temporal events in Caribbean culture history such as subdivisions within pottery typologies during the Ceramic Age (e.g., Troumassoid and Ostionoid) are also likely in need of critical reexamination.

Limitations resulting from the chronometric hygiene protocol could also be circumvented in the future with more detailed reporting and calibration of radiocarbon data, including taxonomic identification of samples, laboratory number, and radiocarbon age. More complete reporting would increase the reliability and, thus, the number of acceptable radiocarbon determinations (i.e., Classes 1 and 2) for many sites and islands across the region, an issue that is still pervasive even in more recent syntheses of data for the Archaic [e.g., (*41*)]. To return to the example of the Hichmans site on Nevis, all nine determinations were designated as Class 3 because they were from unidentified marine shell or reported without sufficient provenience (*24*). If this information was published or made available by the author or the radiocarbon laboratory, then this could possibly aid in refining the colonization estimate for Nevis.

The present database will be further advanced as additional information is made available or if part of the original dated samples were saved and redated. A "best practice" approach to managing legacy dates is to rerun the radiocarbon sample if any part of the original sample remains to improve precision. For other samples, if part of the original specimen remains, it may be possible to identify the taxon to avoid issues such as the "old wood" problem. Regardless, the results show spatiotemporal patterns consistent with previous chronometric hygiene studies, seafaring simulations, and theoretical models of population ecology. Our supporting evidence of previously proposed hypotheses is also potentially falsifiable with additional archaeological evidence. For example, recently published radiocarbon determinations from Grenada suggest a previously unidentified Archaic component (*35*). It is quite possible that expanded research programs on other islands could also push back dates of colonization and strengthen existing chronologies.

CONCLUSIONS

Interpretations of archaeological sites, assemblages, and other remnants of human behavior hinge on developing temporal frameworks largely built on radiocarbon determinations. This study, which involved compiling the largest dataset of radiocarbon determinations from more than 50 islands in the Caribbean, subjecting them to a rigorous chronometric hygiene protocol, and constructing Bayesian models to derive probabilistic colonization estimates, demonstrates that only around half of the currently available radiocarbon determinations are acceptable for chronology building. The paltry number of Class 1 determinations ($n = 10$) is especially concerning as these are considered by scholars elsewhere to be the only form of acceptable samples to use in archaeological research [e.g., (*11*)]. This means that only 0.4% of available 2484 radiocarbon determinations from the Caribbean would be acceptable if the same standards used in other regions were applied here. That many of the radiocarbon determinations in our database were discarded because of a lack of reporting of critical information underscores the importance of transparency when presenting results and conclusions. Given that the average cost of a single radiocarbon determination can be hundreds of dollars, it is not unreasonable to assume that this database represents an investment of around $1 million worth of radiocarbon determinations that have been largely funded by government agencies, not including the associated costs of obtaining sample material. Many radiocarbon determinations are paid for with taxpayer money, and with recent increased scrutiny of publicly funded research in many parts of the world, archaeologists must take responsibility to ensure that their samples are robust, reported in full, and widely available.

Overall, results from chronometric hygiene and Bayesian analysis of acceptable radiocarbon determinations suggest direct movement from South America to the northern Caribbean (Cuba, Hispaniola, and Puerto Rico and the northern Lesser Antilles) that initially bypassed the southern Lesser Antilles, with the exception of Barbados and possibly Grenada, which have evidence—albeit limited—for Archaic colonization. The later colonization estimate for islands in the southern Lesser Antilles supports the southward route hypothesis and the predictions of ideal free distribution and does not support the oft-cited and recently reinvigorated stepping-stone model.

Like many of the current models used by Caribbean scholars to explain past human lifeways that hinge on secure and reliable radiocarbon determinations, these will require further quantitative testing and closer scrutiny of samples used for developing both local and regional chronologies. The analyses presented in this study can also be used to develop testable hypotheses for predicting when those islands not included in our analysis were colonized. Overall, this study demonstrates the need for increased rigor in the reporting of radiocarbon determinations to adequately assess their efficacy and maintain chronological control to ensure that interpretive models are satisfactorily anchored in time and accurately reflect, to the best of our ability, the multitude of cultural behaviors that happened in the past.

MATERIALS AND METHODS

Chronometric hygiene protocol

A chronometric hygiene protocol was applied to critically assess the reliability of radiocarbon determinations in relation to target events. Careful application of stricter criteria improves confidence that the dated radiocarbon event reliably relates to human activity (*5*, *10*, *11*). Dates were placed into four separate classes, the two most acceptable of which were modeled using Bayesian analysis (*30*). Class 1 dates, which fit the most stringent criteria, are from short-lived terrestrial material (i.e., plant remains or juvenile fauna) identified to taxon, terrestrial animal bone identified to taxon and sampled using AMS, and must include both sufficient provenience information (i.e., not from surface contexts, evidence of secure archaeological context) and the processing laboratory name and number. Class 2 dates include charcoal or charred material not identified to taxon, marine shell identified to taxon, and culturally modified shell (e.g., adzes). These dates must also include sufficient provenience information and the processing laboratory number. Class 3 dates are without some component of the above contextual information and also include marine shell dates not identified to taxon, bulk sediment, or shell samples containing multiple individuals, radiometric dates on human bone apatite, or have a radiocarbon age of 300 years B.P. or younger. Radiocarbon dates less than 300 years B.P. were excluded from analysis because the 95% posterior probability would exceed beyond the range of modern age. Unidentified marine shell was given a Class 3 value because some may belong to long-lived species or have other unresolved issues, such as the inbuilt age associated with mobile and/or carnivorous gastropods that ingest older carbon from limestone substrates. Class 4 dates were rejected because they lacked critical information, were not from a secure cultural context, or were originally published as modern dates and rejected by the original author(s). Radiocarbon dates from paleoenvironmental studies were rejected as Class 4 unless a date was collected on anthropogenically introduced plant taxa or were from a secure archaeological context because their association with anthropogenic activity cannot otherwise be demonstrated and, thus, may date contexts before human arrival.

Terrestrial and marine radiocarbon determinations were calibrated using Intcal13 and Marine13, respectively (*30*, *42*). Radiocarbon determinations on human bone were calibrated using a 50%:50% Intcal13/Marine13 curve with a ±12% error to account for the mixed marine and terrestrial diet common in the region. This 50%/50% ratio has been applied in other dietary studies [e.g., (*43*)], although few published studies address how dietary ratio may influence radiocarbon date calibration. Cook *et al.* (*44*) recommend using an error of 10% when groups are not consuming C4 plants; however, we selected a more conservative error of 12% to account for the presence of C4 plants in prehistoric Caribbean diets. Furthermore, marine-based subsistence strategies varied between individuals, across islands or archipelagos, and through time (*45*, *46*). At this stage, it is not possible to develop a template for calibrating human bone other than to say that diets were likely mixed to some degree (*47*, *48*). Future isotopic research on island-specific and temporally specific dietary ratios can be used to refine marine and terrestrial ratios for human bones. In addition, given both the paucity of interisland and intraisland local marine carbon offsets for the Caribbean (*5*, *49*), no local marine reservoir correction (ΔR) was applied to marine determinations, although there should be a concerted effort to obtain these in the future. However, we have applied the standard reservoir correction to marine dates.

Bayesian statistical models

Bayesian statistical models are increasingly used by archaeologists for modeling a range of temporal phenomena, from individual site chronologies to large-scale regional processes, and are particularly useful for radiocarbon datasets because they allow the analyst to incorporate prior information, such as stratigraphy or other known chronological information, into the estimation of probability distributions for groups of radiocarbon determinations. A strength of Bayesian models for archaeological studies is their ability to provide estimated date ranges for undated archaeological contexts, such as the onset, temporal duration, or end of a phenomenon of interest. Three key parameters of any Bayesian model are the prior, the likelihood, and the posterior. In archaeological applications, the prior is any chronological information or observations that are inferred before any radiocarbon data are collected or processed (e.g., stratigraphy), the likelihood is information obtained from the calibrated radiocarbon date range, and the posterior is an estimated calendar date range expressed probabilistically as the highest posterior density (HPD) region based on the relationship between the prior and likelihood (*30*). An evaluation of how well the model fits the radiocarbon data is expressed quantitatively as an agreement index, with agreement indices over 60% being the commonly accepted threshold for a good fit (*50*).

Following recent Bayesian approaches to island colonization modeling in the Pacific [e.g., (*40*, *51*–*53*)], here we model the colonization of the Caribbean islands using single-phase Bayesian models in OxCal 4.3.2 (*30*). This method involves combining radiocarbon dates from multiple strata and sites into a single group with the goal of providing a simple structural framework to estimate the onset of colonization using the collective dates for the island. Using this approach, all uncalibrated conventional radiocarbon age determinations were grouped into a single unordered phase by island (table S4) using the Sequence, Boundary, and Phase functions in OxCal. The model then calibrates these determinations based on prior information (other early dates in the Phase), and the modeled range of the Boundary start provides the colonization estimate. Here, we provide both 68 and 95% HPD probabilities for these colonization estimates, and all date ranges were rounded outward to the nearest five using OxCal's round function (*54*).

Nearly all Class 2 determinations are from potentially long-lived species or unidentified wood samples and present inbuilt age problems. To address this issue, we treated each of these radiocarbon determinations as having a 100% probability of including some amount of inbuilt age using an Exponential Outlier (Charcoal) model using the Charcoal_Outlier model (*31*, *55*). The prior assumption in this type of model is that the correct age of the modeled events is younger than the unmodeled calibrated dates by some unknown amount of time. Thus, the Charcoal_Outlier model is expected to produce somewhat younger age estimates (*31*). We selected a 100-year outlier model because although Caribbean peoples were likely using dry scrub forest taxa, many of which were slow-growth species, use of these trees for fuelwood likely involved coppicing, which would have sustained forests while providing younger limbs for anthropogenic use. Commonly recovered tree species include lignum vitae (*Guaiacum* sp.), buttonwood (*Conocarpus erectus*), caper tree (*Capparis* sp.), strong bark (*Bourreria* sp.), wild lime (*Zanthoxylum fagara*), and mangrove (*56*). Given this ethnobotanical information, we elected to use a 100-year outlier model.

Sensitivity analyses

A large proportion of our dataset is composed of radiocarbon determinations on unidentified wood and wood charcoal that likely have unknown inbuilt ages. Thus, the modeled date estimates derived from these samples may also be too old. To address this, we modeled each island with unidentified wood samples in three ways: (i) as a simple single-phase models with no additional parameters; (ii) treating each radiocarbon determination as having 100% probability of having between 1 and 100 years of inbuilt age using a Charcoal_Outlier model; and (iii) treating each radiocarbon determination as having 100% probability of having between 1 and 1000 years inbuilt age using a Charcoal_Outlier model (table S4; see Supplementary Materials) (*31*). Assuming a 100% probability of samples having inbuilt age is intentionally conservative as not all samples may have considerable inbuilt age.

In another set of sensitivity analyses, Cuba was modeled with and without legacy dates—radiocarbon determinations with large standard errors (e.g., >100 years)—because, although imprecise, these samples likely still provide an accurate measurement of the target event when derived from secure archaeological contexts. Bayesian modeling accounts for imprecision of legacy dates and can still produce acceptable models (*54*). To test the efficacy of incorporating legacy dates, we modeled Cuba with and without legacy dates.

The third set of sensitivity analyses was to test how the model for Puerto Rico improves when modeled with fewer radiocarbon determinations. Modeling all 445 radiocarbon determinations does not produce an acceptable model, but the model agreement increases when fewer dates are modeled (tables S5 and S6; Supplementary Materials). In addition, the oldest radiocarbon determination in the Phase does not have an acceptable agreement index until it is only modeled with 100 radiocarbon determinations.

Last, we tested how islands with many younger dates potentially skew the models and produce younger colonization estimates. To test this, we modeled Trinidad and Puerto Rico using the Tau Boundary function in OxCal, which exponentially weights radiocarbon determinations at one end of the grouping.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/12/eaar7806/DC1

Supplementary Text
Table S1. Radiocarbon determinations from 55 Caribbean islands with their assigned class value.
Table S2. The 100-year outlier model results and parameters for 26 islands.
Table S3. The 100-year outlier model plots with 95% probability ranges.
Table S4. SQL code for the 100-year outlier models, 1000-year outlier models, and single-phase models.
Table S5. Modeled colonization estimates for Puerto Rico with a decreasing number of dates.
Table S6. Single-phase model results and parameters for Puerto Rico with a decreasing number of dates.
Table S7. Sensitivity analyses results.
Table S8. The 1000-year outlier model results and parameters for 26 islands.
Table S9. The 1000-year outlier model plots with 95% probability ranges.
Table S10. Single-phase model results and parameters for 26 islands.
Table S11. Single-phase model plots with 95% probability ranges.
Table S12. Originally reported sample materials with current taxonomic identification.
Table S13. Radiocarbon laboratory abbreviation, name, and country of operation.
Table S14. Bibliographic information for radiocarbon determinations.
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