

**Six centuries of adaptation to a challenging island environment: AMS <sup>14</sup>C dating and stable isotopic analysis of pre-Columbian human remains from the Bahamian archipelago reveal dietary trends**

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## Abstract

The limestone islands of the Bahamian archipelago provide a challenging environment for human settlement, one that was not taken up until after AD 700. The analysis of human skeletal remains offers new insights into how this challenge was met. A substantial program of AMS  $^{14}\text{C}$  dating on pre-Columbian humans ( $n = 66$ ) provides a robust chronological framework for the period ca. AD 1000–1600, with the latter date suggesting the possible persistence of an indigenous Lucayan presence on the islands for some decades later than previously thought. Associated stable carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) isotope analyses imply an initial focus on near-shore marine resources that seems to have rapidly led to their local over-exploitation, resulting in a shift towards horticulture based mainly on root crops. The Medieval Warm Period is very likely to have been a factor in the initial settlement of the islands; the impact of the Little Ice Age is less clear, with no clear changes in either  $\delta^{13}\text{C}$  or  $\delta^{15}\text{N}$ . Strontium isotope results are consistent with an origin of most individuals within the archipelago, with a limited (but potentially important for maintaining connections) presence of incomers from the Greater Antilles, and perhaps even further afield. Despite the relatively short history of pre-Columbian occupation, Lucayan adaptations to the Bahamian archipelago were dynamic and demonstrate resilience in the face of both human resource depletion and climate change.

**Keywords:** carbon, nitrogen, strontium isotopes; resource over-exploitation; resilience; Caribbean

## Highlights

- Initial settlement of the Bahamian archipelago coincides with the Medieval Warm Period
- Over-exploitation of near-shore resources offset by increased use of terrestrial resources
- Even small human populations can have an impact on ‘pristine’ environments
- Pre-Columbian Lucayan populations were resilient to these changes

## 1. Introduction

The limestone islands of the Bahamian archipelago were not only the last islands to be settled in the Caribbean culture area, but some of the last in the world. Comprising The Bahamas and Turks and Caicos Islands (TCI), the archipelago is made up of over 740 islands, with thousands of small sandy cays (Figure 1). Despite their proximity to the large Greater Antillean islands, with occupation extending back to at least ca. 4000–5000 BC (Keegan and Hofman, 2017), the archipelago appears not to have been occupied before ca. AD 700, initially by seasonal forays from the neighboring large islands (Carlson, 1999; Keegan and Hofman, 2017; Sears and Sullivan, 1978; Sinelli, 2010; 2013). The delay in more permanent settlement, and the timing of its appearance from ca. AD 800, may be related to the end of a long period of aridity (Kjellmark, 1996; Nyberg et al., 2001; 2002), combined with a challenging environment, with few sources of fresh water, generally limited soil development, no source of hard stone for tools and an impoverished terrestrial fauna. Their comparatively small size also makes their ecosystems more precarious and susceptible to disruption (MacArthur and Wilson, 1967; Ricklefs and Bermingham, 2007). Occupation was relatively short-lived, with the islands reportedly being depopulated by the early 16<sup>th</sup> century. This constrained island setting and restricted timescale of human presence provides an excellent opportunity to address a range of questions relating to island adaptations (Fitzhugh and Hunt, 1997).

In this paper we take a bioarchaeological approach, focusing on isotopic analyses of pre-Columbian human remains from the Bahamian archipelago, and supported by a robust chronological framework provided by 57 new and nine previously published radiocarbon dates (n=66). Employing stable carbon and nitrogen isotope measurements on human skeletal remains, we address spatiotemporal dietary variability in the use of C<sub>3</sub> and C<sub>4</sub> crops and marine foods in light of the different climatic regimes of the archipelago and the impacts of the Medieval Warm Period (MWP) and the Little Ice Age (LIA). Root crops, for example, would be favoured by the wetter, warmer conditions of the MWP, while drier conditions of the southern part of the archipelago would favour maize, particularly during the LIA. Aridity is also known to increase  $\delta^{15}\text{N}$  values in plants (Amundson et al., 2003) and hence in the animals consuming them, including humans. Marine resources would provide the most reliable source of protein at all times given the impoverished terrestrial fauna, and also act as a buffer during periods with poor crop yields. Nevertheless, variability might be expected in their use, both spatially and temporally, depending on the availability and viability of other options. Our approach enables a high-

resolution investigation of these themes within an insular circum-Caribbean setting. We also present the first strontium isotope dataset on humans from The Bahamas, addressing the extent to which continued movement of individuals from the Greater Antilles featured as a strategy to increase the resilience of the socioeconomic system (Adger, 2000).

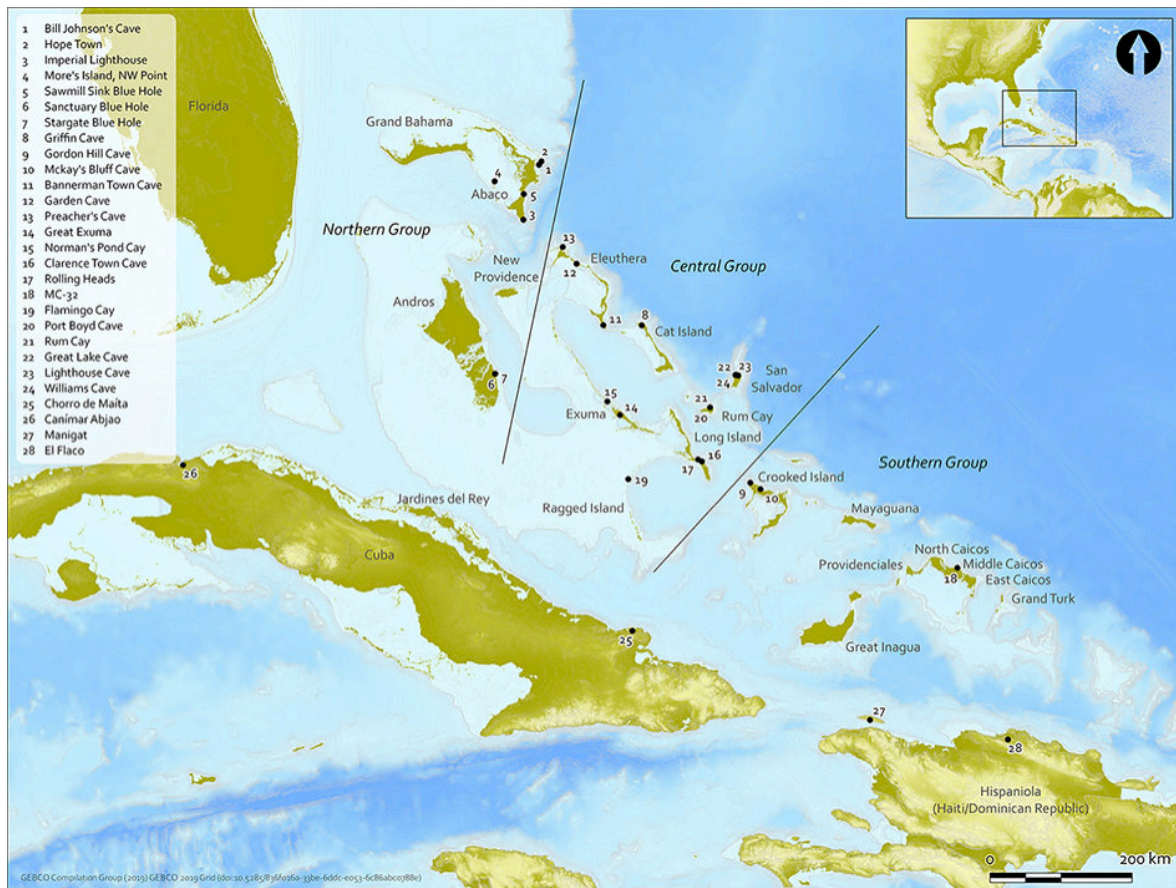


Figure 1. Map showing the islands represented in the study and locations of sites sampled. Sites on Cuba and Hispaniola providing comparative data are also shown.

### 1.1 Synopsis of archaeological context

The earliest known sites in the Bahamian archipelago are Coralie on Grand Turk and Three Dog Site on San Salvador, although to some extent this may reflect the greater amount of research effort – and radiocarbon dating – that these islands have seen, particularly San Salvador (Berman and Gnivecki, 1995; Blick and Dvoracek, 2011; Carlson, 1999; Keegan and Hofman, 2017). Pottery styles have long linked the early settlement of TCI with Hispaniola, most likely the north coast of Haiti based on proximity, while the north coast of central and southern Cuba is a good candidate for the initial settlement of the south-central Bahamas (Berman et al., 2013; Granberry, 1956; Keegan, 1997; 2007; Keegan and Hofman, 2017). However, recent DNA evidence has

linked The Bahamas more strongly with Hispaniola (Fernandes et al., 2020; Nägele et al., 2020; Schroeder et al., 2018), but this may be in part due to the limited number of comparative samples of appropriate date (i.e., Late Ceramic, AD 600–1492) from Cuba. Despite its proximity to the northern Bahamas, there is no firm material evidence for pre-Columbian contacts with Florida (Berman, 2011), nor is there any genetic evidence of admixture with North American Amerindians (Fernandes et al., 2020; Nägele et al., 2020; Schroeder et al., 2018).

Regardless of their origins, the early settlers – the ancestors of the Lucayans who occupied the islands when they were first ‘discovered’ by Columbus in 1492 – brought with them a range of skills and materials, including a suite of crops ultimately derived from lowland South America, the source of various population movements into the Caribbean (Fernandes et al., 2020; Nägele et al., 2020; Rouse, 1992; Schroeder et al., 2018). The most important root crops would have been cassava or manioc (*Manihot esculenta*), supported by sweet potato (*Ipomoea batatas*), yam (*Dioscorea trifida*), cocoyam (*Xanthosoma* sp.) and coontie or zamia (*Zamia* sp.). While maize (*Zea mays*) undoubtedly formed part of this imported larder, there has been much debate about its dietary importance in both The Bahamas specifically, and in the Caribbean more broadly. Long seen as relatively peripheral (Rouse, 1992), increasing evidence for its use suggests that the position of maize may be in need of re-evaluation (Berman and Pearsall, 2008; 2020; Chinique de Armas et al., 2015; Ciofalo et al., 2018; 2019; 2020; Figueredo, 2015; Lane et al., 2008; Mickleburgh and Pagán-Jiménez, 2012; Newsom and Wing, 2004; Sullivan et al., 2019). That said, much of this new evidence relates to maize phytoliths and starch grain residues recovered from stone and shell tools, ceramic griddles and human dental calculus, certainly indicating its presence but not necessarily reflecting its proportional contribution to diets. Actual palaeoethnobotanical evidence remains stubbornly rare, with the only examples from The Bahamas and TCI being two charred maize kernels from Pigeon Creek, San Salvador (Berman and Pearsall, 2020), and two charred cobs Preacher’s Cave, Eleuthera (Carr et al., 2006). One interesting suggestion to account for this is that maize was reserved for the élite, at least those of the Taíno *cazicagos* (chiefdoms) of Hispaniola (Newsom, 2016; Newsom and Deagan, 1994). Whether this may have been a factor for the Lucayans of the Bahamian archipelago is unknown, nor is this something that is possible to address in the present study, as the nature of the human skeletal material and its recovery precludes sufficient contextual associations to pose questions relating to socioeconomic status differentiation.

After ca. AD 800, an independent Lucayan culture can be recognized on the basis of locally produced Palmetto and related wares (Berman et al., 2013; Sears and Sullivan, 1978) and a distinct style of the ceremonial seats known as *duhos* (Ostapkowicz, 2015). Adaptations and material culture appear to have been similar across the archipelago, although many islands have seen only limited investigation. These developments were abruptly curtailed with the arrival of Columbus in 1492. Within a few short decades, the Lucayan population was decimated by introduced disease and forced removal into slavery. In the first two decades of the 16<sup>th</sup> century, Lucayan slaves were especially sought after as pearl divers for the lucrative industry off the coast of Venezuela (Granberry, 1979-81; Berman and Gnivecki, 2019). In one account, two Spaniards – Francisco Gordillo and Toribio de Villafranca – reportedly captured 900 Lucayans from the archipelago in 1514–1517, confining them in ‘pens’ on Andros before shipment to Hispaniola. Over half died before supplies and ships arrived on Andros (Hoffman, 1990). By 1520 the archipelago was thought to be entirely uninhabited (Keegan, 1992; Sauer, 1966) and to have remained so until the arrival of a group of English puritans known as the Eleutheran Adventurers in 1648 (Craton and Saunders, 1992; Miller, 1945).

### *1.2 Environmental context and human impact*

While all the islands have good access to marine resources, especially those of shallow-water reef systems and seagrass beds, they vary in their agricultural potential for the staples manioc and maize. Islands with the deepest pockets of soil may be more suitable for root crops, with the caveat that the climate of the archipelago’s northernmost islands may be less suited to manioc due to cool winter temperatures, and so might favor maize, thus leading to a latitudinal gradient (Sears and Sullivan, 1978). Since these are C<sub>3</sub> and C<sub>4</sub> crops respectively, their  $\delta^{13}\text{C}$  values will be very different, though with the added complication of the consumption of marine foods, the values of which overlap with those of C<sub>4</sub> plants (Keegan and DeNiro, 1988). The generally thin, nutrient-impooverished soils would likely have been susceptible to rapid exhaustion even before the islands’ forests were denuded in the eighteenth and nineteenth centuries, and so we might expect changes in the subsistence economy over time (e.g., greater consumption of marine foods as crop yields declined). As detailed below, there is also significant climate change in the form of the LIA that would have impacted upon terrestrial productivity in particular. Thus, subsistence practices may well have changed over even the comparatively short history of settlement in the Bahamian archipelago, based both on the potentially rapid depletion of marine and terrestrial resources (including soil fertility) and on climate change.

The degree to which the islands were transformed by early human presence is currently a matter of active debate, but it may have been considerable (Baisre, 2010; Orihuela et al., 2020). Hutias (*Geocapromys ingrahami*) – a medium size rodent – were endemic to some Bahamian islands but not others, including TCI, to which they were translocated as a food animal (LeFebvre et al., 2019a; 2019b; Oswald et al., 2020). These, along with introduced dogs, could themselves have been agents of landscape change (Campbell et al., 1991). Other animal species became either locally extirpated or extinct (Hastings et al., 2014; Steadman et al., 2007; 2014; 2017; 2020). Nevertheless, in terms of scale, any anthropogenic changes seen in pre-Columbian times pale in comparison to those of the Colonial period, when logging operations denuded the forests of valuable hardwoods such as mahogany (*Swietenia* sp.) and lignum vitae (*Guaiacum* sp.) and large plantations further transformed the landscape.

The period under consideration here, then, extends from ca. AD 700 to ca. AD 1520 (though, as discussed below, there is mounting evidence that a Lucayan presence on some islands may have persisted some decades beyond this). These few centuries witnessed a very dynamic series of historical events, from initial colonization and rapid expansion, before being abruptly curtailed by the arrival of the Spanish. Climate change is also an important factor, as this period encompasses both the MWP and the onset of the LIA (Curtis et al., 2001; Hodell et al., 1991; 2005; Ljungqvist et al., 2012; Nyberg et al., 2001; 2002). In fact, it may have been the extended period of aridity in the first millennium AD that delayed permanent settlement of the Bahamian archipelago, making successful cultivation too high-risk. The increased precipitation at the start of the MWP from ca. AD 800 would have greatly reduced these risks, making the islands more attractive.

Palaeoecological records in sediment cores from a blue hole on Andros in the northern Bahamas provides local evidence for both trends, as well as for human impacts during Lucayan occupation (Kjellmark, 1996). This trend was abruptly reversed with the onset of the LIA from ca. AD 1400 (Miller et al., 2012), with increased aridity and a reduction of 2–3 °C in winter temperatures across the circum-Caribbean (Hodell et al., 1991; 2005; Nyberg et al., 2001; 2002).

## **2. Materials and Methods**

Human bone and tooth samples were obtained from the National Museum of The Bahamas (AMMC); National Museum of Natural History (Smithsonian); Natural History Museum, London; Peabody Museum of Natural History (Yale); and the Turks and Caicos National

Museum. Efforts were made to ensure that distinct individuals were selected by sampling non-duplicating elements, controlled for age (e.g., five adult left humeri and two children's mandibles from Lighthouse Cave, San Salvador). For further information on the sites represented in the project see SI.1 (Figure S1, Table S1).

### *2.1 Radiocarbon dating*

Bone/dentine samples weighing  $\leq 1$  g were shot-blasted to remove surface contaminants, and prepared for AMS  $^{14}\text{C}$  dating and stable isotope analysis using the standard protocols in place at the Oxford Radiocarbon Accelerator Unit in the School of Archaeology, University of Oxford (Brock et al., 2010). All samples, except Stargate, Andros (SGBH-1), and a calcined bone sample from Preacher's Cave, Eleuthera (PC 171A-2, 3) were pretreated following a procedure comprising a decalcification in acid, a base wash, a re-acidification, gelatinization and ultrafiltration. The human remains from Sanctuary Blue Hole, Andros, were coated in a polyurethane preservative upon recovery in the 1990s, while that from Stargate Blue Hole, Andros, was treated with Butvar®, a polyvinyl butyral resin. Given concerns over the ability to ensure complete removal of these contaminants (Brock et al., 2018), teeth from these two sites were targeted for dating at Oxford. As the consolidants were applied with a brush, the tooth roots would have been protected in the mandible or maxilla. Because of the treatment of the Stargate Blue Hole human remains with Butvar®, we also undertook single amino acid dating on the single specimen from this site represented in the project (SGBH-1), which was seen as particularly important because of its potential association of the human remains with a rare example of a small wooden canoe (the dating of which is currently underway). The method involves separation of the underivatized amino acids using preparative liquid chromatography after hydrolysis of the bone collagen to isolate the amino acid hydroxyproline (Devièse et al., 2018).

All samples (collagen or hydroxyproline) were then combusted, graphitized and measured on the AMS. The quality of the collagen or hydroxyproline extracted was monitored by measuring carbon and nitrogen contents (%C and %N) and the atomic ratio of carbon to nitrogen (C:N) that is acceptable in the range 2.9–3.5 in the case of collagen or 4.9–5.1 in the case of hydroxyproline.

Cremation only rarely features in the Caribbean. The project included a rare example of cremated bone from Preacher's Cave, Eleuthera (PC 171A-2, 3) (Carr et al., 2006). The preparation for



calcined bone involves bleaching with several rinses of a 1.5% sodium chlorite solution at pH 4 for 48 hours at room temperature to remove any organics. Any adsorbed carbonates are then removed using several rinses with 1M acetic acid over 24 hr at room temperature. The sample is then reacted with phosphoric acid in vacuum after which it is transferred to a water bath at 50 °C to equilibrate for an hour, before adding acid to the sample and leaving to react for ca. 8 hr. The reaction vessel is then re-attached to the vacuum line, the line evacuated, and a water trap (methanol at -65 °C) placed on the line. The reaction vessel is opened and any CO<sub>2</sub> is transferred to a glass ampoule and sealed for AMS dating (Brock et al., 2010).

## *2.2 Modeling of the radiocarbon dates*

All dates (i.e., the new dates together with those previously published) were corrected for the marine reservoir effect (MRE) (SI.2) and analyzed in OxCal 4.4 using both Bayesian and kernel density estimation (KDE) models (Bronk Ramsey, 2009; 2020; 2017; Lee and Bronk Ramsey, 2012) (see SI.2). KDE models are emphasized since, in the absence of prior information concerning the shape of the distribution of radiocarbon dates, these are more appropriate than Bayesian models (Bronk Ramsey, 2017). Since they still constrain start and end dates, both modeled and unmodeled medians of the 95.4% confidence intervals are used to explore diachronic trends in  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ . All error ranges are quoted as 95.4% unless otherwise noted.

## *2.3 Stable carbon and nitrogen isotope analysis*

Stable carbon and nitrogen isotopes were analyzed separately using the same collagen prepared for AMS dating. Samples were measured in duplicate on a Sercon 20/22 Isotope Ratio Mass Spectrometer (IRMS) in the School of Archaeology, University of Oxford, with the mean of the two runs reported here. Alanine was used to correct for machine drift, with additional alanine (-27.11‰ and -1.56‰ for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ , respectively) and USGS40 (-26.4‰, -4.5‰) and USGS41 (+37.6‰, 47.6‰) standards providing a three-point calibration relative to international standards VPDB and AIR for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ , respectively (Coplen et al., 2006). Instrument precision is on the order of  $\pm 0.2\text{‰}$  for both  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  based on repeated measurements of laboratory standards.

## *2.4 Correcting for the marine reservoir effect*

Calibration of the radiocarbon dates is complicated by the marine reservoir effect (MRE). Based on the high proportion of fish recovered from Lucayan sites relative to terrestrial fauna, and the stable carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) isotope results on human remains, it is clear that Lucayans relied heavily on marine resources, especially for the protein component of their diets (Keegan and DeNiro, 1988; Stokes, 1998). It is this component that contributes most strongly to the carbon found in the collagen fraction used for AMS dating and stable isotope analysis (Ambrose and Norr, 1993; Jim et al., 2006). While  $\delta^{13}\text{C}$  values are often used to estimate the proportion of marine protein in an individual's diet, this is problematic in The Bahamas and TCI due to the presence of maize, a  $\text{C}_4$  crop with elevated  $\delta^{13}\text{C}$  values that overlap with those of marine organisms. Maize is known to have been present in parts of the archipelago since at least AD 800 (Berman and Pearsall, 2008; 2020; Ciofalo et al., 2018; 2019; 2020), forming part of the suite of crops brought by the original colonists. The problem is exacerbated by the fact that reef fish (and many sea turtles) are unusually  $^{13}\text{C}$ -enriched compared to other marine ecosystems, making them indistinguishable from maize (Fry et al., 1982; Keegan and DeNiro, 1988; Schoeninger and DeNiro, 1984) (see SI.6).

In many contexts human  $\delta^{15}\text{N}$  values would allow separation between the dietary contributions of plant and animal foods, particularly marine species, as they are operating at a much higher trophic level (Keegan and DeNiro, 1988; Minagawa and Wada, 1984; Pestle, 2013a; Hedges and Reynard, 2007; Schoeninger and DeNiro, 1984; Schoeninger et al., 1983). But again, coral reefs (and seagrass meadows) present difficulties, as they are unusually  $^{15}\text{N}$ -depleted compared to other marine systems as a result of the importance of nitrogen-fixing blue-green algae at the base of the food chain (de la Morinière et al., 2003; Schoeninger and DeNiro, 1984; Yamamuro et al., 1995). This reduces – though not necessarily completely obviating – its use as an additional proxy for the consumption of higher-trophic-level foods. Further complicating the picture is the possibility that maize may have been fertilized to improve, or at least sustain, crop yields, resulting in a degree of  $^{15}\text{N}$ -enrichment (Szpak et al., 2012).

Measurements of  $\delta^{13}\text{C}$  in the mineral component of bone, bioapatite, could potentially help distinguish between marine fish and maize, as it reflects total diet, including carbohydrates, rather than emphasizing dietary protein as do measurements on collagen (Ambrose and Norr, 1993; Jim et al., 2006). A small number of  $\delta^{13}\text{C}$  analyses on bone bioapatite of Lucayan remains have been undertaken previously (Stokes, 1998), but while there is still an ongoing debate on the subject, there are issues with diagenesis that could make these data unreliable (Garvie-Lok et al., 2004;

Kellner and Schoeninger, 2007; Kreuger, 1991; Koch et al., 1997; Lee-Thorp and Sponheimer, 2003; Nelson et al., 1986; Shin and Hedges, 2012; Wang and Cerling, 2004). The potential for exogenous carbonates to affect measurements is particularly germane in the pure limestone geology of the Bahamian archipelago. It is for these reasons that we do not use the available  $\delta^{13}\text{C}$  measurements on bioapatite. In addition, while Bayesian modeling of diets has been attempted elsewhere in the Caribbean (cf. Chinique de Armas et al., 2016; Pestle and Laffoon, 2018), we feel that uncertainty regarding the  $\delta^{15}\text{N}$  values of the key plant crops (which would change dramatically if manuring was practiced) and the high variability in the  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of marine species make this premature for The Bahamas at this point (see SI.4).

The issue of the marine reservoir effect (MRE) is particularly important given the restricted time range with which we are dealing in the Bahamian archipelago, encompassing no more than seven or eight centuries. Against this, the average global MRE for the Holocene is around 500 yr (Heaton et al., 2020). Thus, an individual acquiring all of their protein from marine sources would present a radiocarbon date that was ca. 500 years too old. Obviously this would seriously impact on any interpretation. The existing human remains, often recovered in the late nineteenth or early twentieth centuries, or from disturbed contexts, provide no opportunities to date clearly associated terrestrial (or marine) grave offerings that would provide another means of addressing the extent of the MRE (through the dating of so-called ‘perfect pairs’); a single exception is presented in SI.2 (Figure S2). A local  $\Delta\text{R}$  offset of  $-199 \pm 87$  yr is applied, based on radiocarbon dates for the 10 geographically proximal, known-age pre-1950 marine shells in CALIB’s Marine Reservoir Database, <http://calib.org/marine/> (Reimer and Reimer 2001; see Table S4). This includes new results recently reported by DiNapoli et al. (2021) for a number of Bahamian islands. Because of substantial changes in the calculation of the new Marine20 calibration curve and associated  $\Delta\text{R}$  values and their uncertainty (Heaton et al., 2020), this supersedes previously proposed  $\Delta\text{R}$  values for the Caribbean (e.g., Broecker and Olson, 1961; Cooper and Thomas, 2011; Wagner et al., 2009).

### *2.5 Strontium isotope and concentration analysis*

For strontium concentration and isotope analyses, the outer layers of the tooth enamel fragments were first carefully removed using a diamond drill. They were then cleaned using 0.1M acetic acid for 30 minutes, rinsed three times with MilliQ water and left to dry overnight at 50°C. Strontium isotope ratios were measured on a Nu MC-ICP-MS at the Université Libre de

Bruxelles after extraction of the strontium from the samples using Sr-spec resin. Repeated measurements of the NBS987 standard yielded  $^{87}\text{Sr}/^{86}\text{Sr} = 0.710239 \pm 0.000026$  (2SD for 14 analyses). Strontium concentrations were obtained on a Thermo Scientific Element 2 sector field ICP mass spectrometer at the Vrije Universiteit Brussel in low ( $^{86}\text{Sr}$  and  $^{88}\text{Sr}$ ) and medium ( $^{43}\text{Ca}$  and  $^{44}\text{Ca}$ ) resolution using Indium (In) as an internal standard and external calibration against three ISO certified standards from the Bureau of Analyzed Samples (Middlesborough, UK): CCB01 cremated bone apatite; CRM512 dolomite; and ECRM782-1 dolomite. Based on repeated digestion and measurement of this reference material, the analytical precision (1SD) of the procedure outlined above is estimated to be better than 5%. Strontium concentration results are normalized to a calcium concentration of 40%. The single calcined bone sample was prepared according to the methods set out in Snoeck et al. (2015).

## 2.6 Statistical analysis

Data were assessed for normality using Shapiro-Wilk tests, and then analyzed using parametric (Student's *t*-test; ANOVA) or non-parametric (Mann-Whitney *U*-test; Kruskal-Wallis ANOVA) statistics as appropriate, using two-sided tests with a significance level of  $\alpha = 0.05$ . A Bonferroni post-hoc correction was applied when multiple groups were compared simultaneously.

## 3. Results

### 3.1 Radiocarbon dating results and calibration

We obtained 57 new AMS  $^{14}\text{C}$  dates on pre-Columbian human remains. This excludes two historic dates – one on a human and the other on a dog (see SI.3) – and an additional four samples that failed to yield sufficient collagen for dating. Combining the new results with previously published dates provides a total of 66 determinations made directly on human remains from the Bahamian archipelago (Fernandes et al., 2020; Schaffer et al., 2012; Steadman et al., 2007; Stokes, 1998) (Tables S2, S3). Two petrous bones from Sanctuary Blue Hole that were part of an ancient DNA study were dated at Pennsylvania State University (Fernandes et al., 2020). Their location inside the cranium should have offered protection from any surface coatings (see section 2.1). Two previously published dates on human long bones from Sanctuary Blue Hole (Beta-268510,  $520 \pm 40$  BP) and Stargate Blue Hole (Beta-268511,  $620 \pm 40$  BP) (Hastings et al., 2014) are excluded as potentially being affected by preservatives; in addition, these may duplicate the

same individuals dated using cranial elements (teeth and petrous bones). Also excluded are three unpublished dates on human long bones from Sanctuary (on file with M. Pateman): SBH-9, Beta-260756 ( $660 \pm 40$  BP); SBH-4, Beta-260754 ( $650 \pm 40$  BP); and SBH-6, Beta-260755 ( $630 \pm 40$  BP). Of these, SBH-4 and SBH-6 also have dates on teeth done as part of this project, OxA39243 ( $456 \pm 18$  BP) and OxA-39127 ( $584 \pm 20$  BP). Given the context of the site (i.e., the remains were not intact skeletons), it is not entirely certain that the long bones and teeth belong to the same individuals; nevertheless, taking these and the previously published dates into account, it is clear that the new Oxford determinations are significantly later than those obtained at Beta-Analytic. We strongly suspect that the latter dates reflect contamination with old carbon introduced by the conservation treatment.

As discussed in Methods (section 2.4), the correction for the MRE is particularly complex in the study area. Based on measurements on reef fish from archaeological sites on TCI and on modern fish and shellfish from The Bahamas, the marine endmember for the collagen  $\delta^{13}\text{C}$  value of a human consumer is taken to be ca.  $-5\text{‰}$  (i.e., 100% marine diet), while that of a purely  $\text{C}_3$  terrestrial consumer is taken to be ca.  $-20\text{‰}$ , based on adjusted measurements on root crops (Keegan and DeNiro, 1988; Pestle, 2010; Stokes, 1998) and on archaeological tortoise (*Chelonoidis alburyorum*) remains from Abaco (Hastings et al., 2014) (for details see SI.4). The endmember for the bone collagen of a consumer of a pure  $\text{C}_4$  maize diet is  $-6\text{‰}$  based on modern plants adjusted by  $+1.5\text{‰}$  for a fossil fuel effect (Keeling, 1979), highlighting the unusual near-equivalence with the marine endmember, which in many other contexts would be ca.  $-12\text{‰}$  (Richards and Hedges, 1999). The resulting estimated contribution of marine protein to human diets from The Bahamas and TCI ranges between ca. 20% and 80%, averaging  $46 \pm 10\%$ .

To further address the ambiguity caused by the essential equivalence of  $\delta^{13}\text{C}$  values in maize and reef fish, we take advantage of the moderate but statistically significant positive correlation between  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values (Figure 2;  $r^2 = 0.202$ ,  $p < 0.001$ ,  $n = 60$ ). First, the proportion of marine foods is estimated using the aforementioned  $\delta^{13}\text{C}$  endmembers using simple linear extrapolation. This is then modified using the standardized residuals of the linear regression model. The estimate is left unchanged for those values with residuals between  $-1.0$  and  $+1.0$ ; those above or below this are adjusted by  $-10\%$  and  $+10\%$ , respectively, while the three results with residuals above  $2.0$  are adjusted by  $-20\%$  (see Table S2). While this correction results in lower precision for individual dates (particularly in light of the abovementioned high uncertainty in  $\Delta R$ ), it is seen as the most realistic solution possible at this stage. It is provisional and bespoke

for this dataset, so that any further application would need to be treated cautiously. Infants are not adjusted because of the impact of nursing on their  $\delta^{15}\text{N}$  values (Schurr, 1998). In the case of the single cremated bone sample from Preacher’s Cave (for which no dietary  $\delta^{13}\text{C}$  measurement is possible), we use the mean of 46% for all other individuals. In all cases  $\pm 10\%$  uncertainty is added to the estimates when entered into OxCal 4.4 for calibration using mixed terrestrial (IntCal20; Reimer et al., 2020) and marine (Marine20; Heaton et al., 2020) calibration curves. The resulting calibrated, MRE-corrected dates are shown in Figure 3.

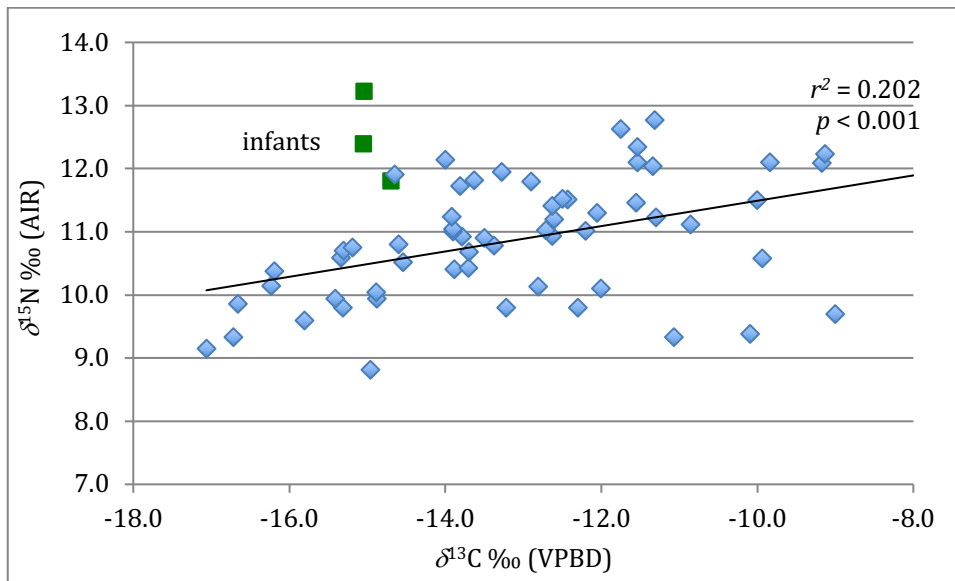


Figure 2. Residuals from regression model ( $\delta^{13}\text{C} = -23.9644 + 1.0041(\delta^{15}\text{N})$ ) are used to adjust the estimated %marine in individual human diets as described in the text (and see Table S2). The green squares denote infants/young children and are excluded from the model since their  $\delta^{15}\text{N}$  values are potentially subject to a nursing effect.

Once corrected for the marine reservoir effect, the unmodeled individual dates range between AD 710–1015 (OxA-37863) and AD 1435–1670 (OxA-39125). As an illustration of the importance of taking the MRE into account, the same two dates calibrated without this correction are AD 657–775 and AD 1319–1418. The KDE model notably constrains the early end of the range, with the same two earliest and latest dates modeled as AD 930–1160 and AD 1515–1680 respectively.

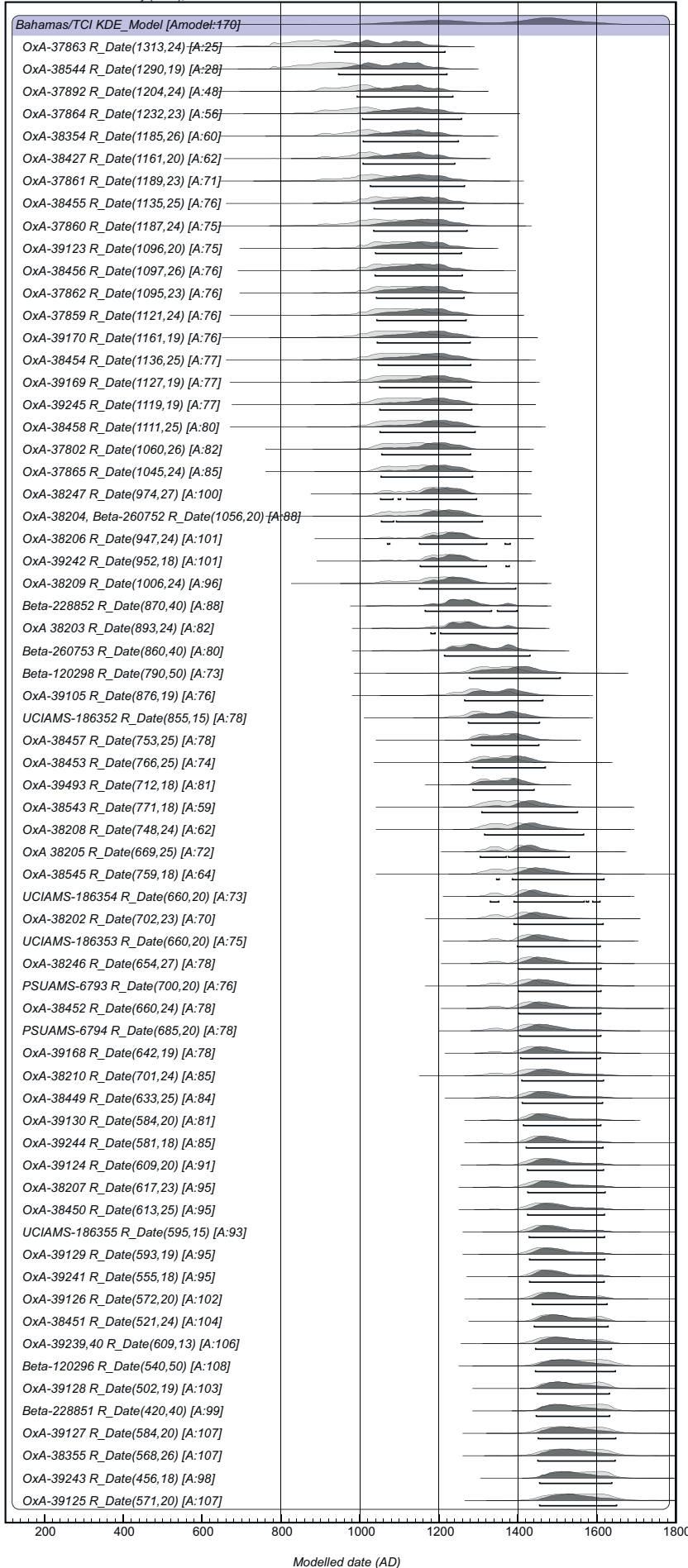


Figure 3. KDE model of reservoir-corrected modeled AMS <sup>14</sup>C dates on human remains from The Bahamas and TCI using mixed terrestrial and marine curves (sources: this paper; Fernandes et al., 2020; Schaffer et al., 2012; Steadman et al., 2007; Stokes, 1998). OxA-37863 and OxA-38544 have agreement indices well below the recommended 60%, but are retained here, since: 1) OxA-37863 fits within a group of early dates on human remains from Lighthouse Cave, San Salvador (Table S4); and 2) given the large number of dates in the model (n = 66), at least three dates would be expected to fall below the 60% criterion (which equates to 5% probability) even if they belonging to the defined phase. Furthermore, low agreement indices only mean that the dates do not fit well within a single phase of activity; they do not invalidate the dates themselves.

### 3.2 Stable carbon and nitrogen isotope results

Excluding three infants/young children potentially subject to a nursing effect (Schurr 1998), the isotopic results average  $-13.2 \pm 2.1\text{‰}$  ( $n = 62$ ) and  $10.9 \pm 0.9\text{‰}$  ( $n = 60$ ) for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ , respectively (two samples lack associated  $\delta^{15}\text{N}$  measurements). The infants/young children average  $-14.9 \pm 0.2\text{‰}$  and  $12.5 \pm 0.7\text{‰}$  ( $n = 3$ ) for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ , respectively. Excluding these, there is a low but statistically significant positive correlation between  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  ( $r^2 = 0.202$ ,  $p < 0.001$ ,  $n = 60$ ) (Figure 4). As noted above, this is important for the MRE correction in that it suggests that, despite the confounding factors of maize consumption and the unusual isotopic ecology of reef ecosystems,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  are still tracking marine dietary contributions to some extent.

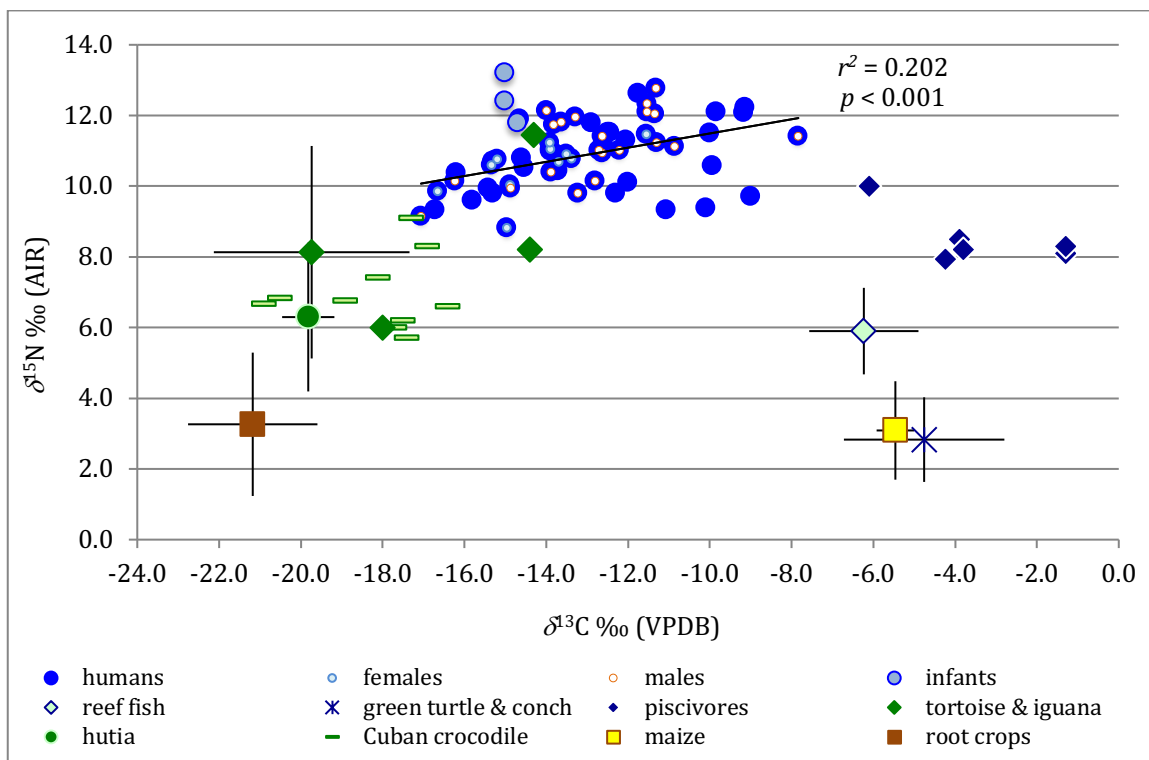


Figure 4. Relationship between  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values for Bahamian humans and comparative fauna and adjusted flora (for details see SI.4; error bars are  $\pm 1\text{SD}$ ). The regression line ( $r^2 = 0.202$ ,  $p < 0.001$ ,  $n = 61$ ) excludes the three infants, potentially subject to a nursing effect. The large blue circles represent all post-weaning humans, with the smaller inset symbols identifying sex where available. The Bahamian results stand out in a comparison with other Caribbean islands in their higher average  $\delta^{13}\text{C}$  values, interpreted as reflecting greater use of reef resources (Table S6, Figure S3).



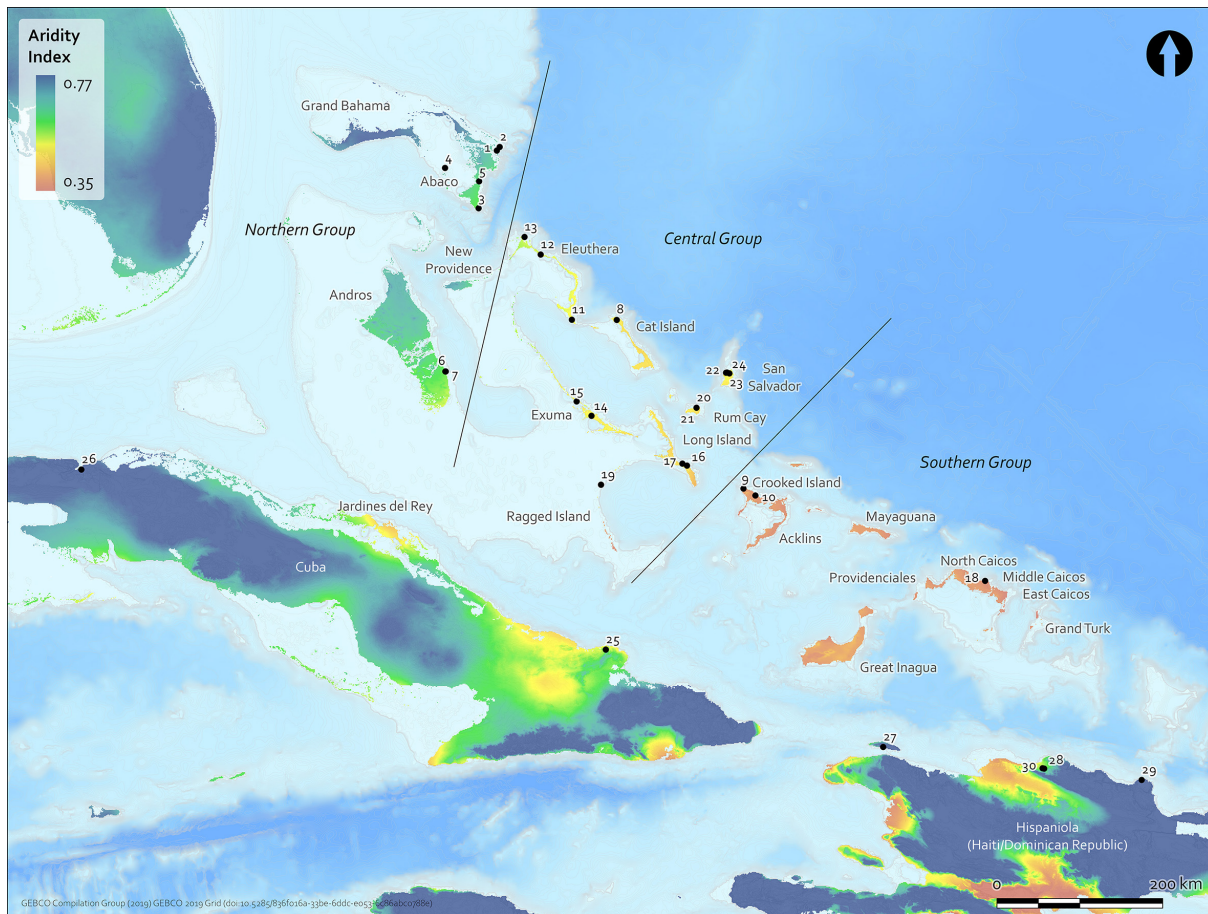


Figure 5. Aridity Index map of the Bahamian archipelago, based on data in Trabuco and Zomer (2019; cf. UNEP, 2007). A linear stretch has been applied to the range of aridity index values for the Bahamas/TCI to highlight subtler distinctions within the Dry Sub-Humid and Semi-Arid zones that are most relevant for horticulturalists (for further details see SI.5).

Spatial trends in the dates are investigated through a comparison of the northern (Abaco and Andros), central (Eleuthera, Cat Island, Exumas, Long Island, Ragged Island, Rum Cay, and San Salvador), and southern (Crooked Island and Middle Caicos) island groups following a climatic latitudinal trend (Figure 5; note that our inclusion of Crooked Island and Acklins Island – the latter not represented in our study – in the southern group differs from previous classifications (Keegan, 1992; Sears and Sullivan, 1978), which included these in the central group). The UNEP (2007; Verbist et al., 2010) climate classification zones range from Humid Sub-Humid in the northern islands to Semi-Arid in the central and southern islands (Figure S5), which would be expected to have an impact on horticultural practices. If so, they are not evident isotopically, as there is no significant difference in median  $\delta^{13}\text{C}$  values between the three island groupings (Kruskal-Wallis test,  $H = 1.56$ ,  $p = 0.459$ ), nor do mean  $\delta^{15}\text{N}$  values differ (ANOVA,  $F = 0.750$ ,  $p = 0.478$ ) (Figure 6, see also SI.5; Figures S6, S7). It is the southern islands, however, that would be expected to most clearly show the effects of aridity on the selection of  $\text{C}_3$  vs.  $\text{C}_4$  crops

and on  $\delta^{15}\text{N}$  values, and this group is the least well represented here. TCI in particular is poorly represented, with only a single sample from Middle Caicos, as very few human remains have been recovered from these islands. Nevertheless, at this point there is no clear spatial patterning in the isotopic results. This is particularly striking since all of the individuals in the southern group have modeled median dates post-AD 1400, and so were potentially affected by the additional aridity of the LIA (Figure S8). This might be expected to result in higher  $\delta^{15}\text{N}$  values, and a greater focus on maize as a crop, leading to higher  $\delta^{13}\text{C}$  values. However, no such trends are apparent even when comparing only those individuals with post-AD 1400 median dates from the three island groupings (Figures S9, S10).

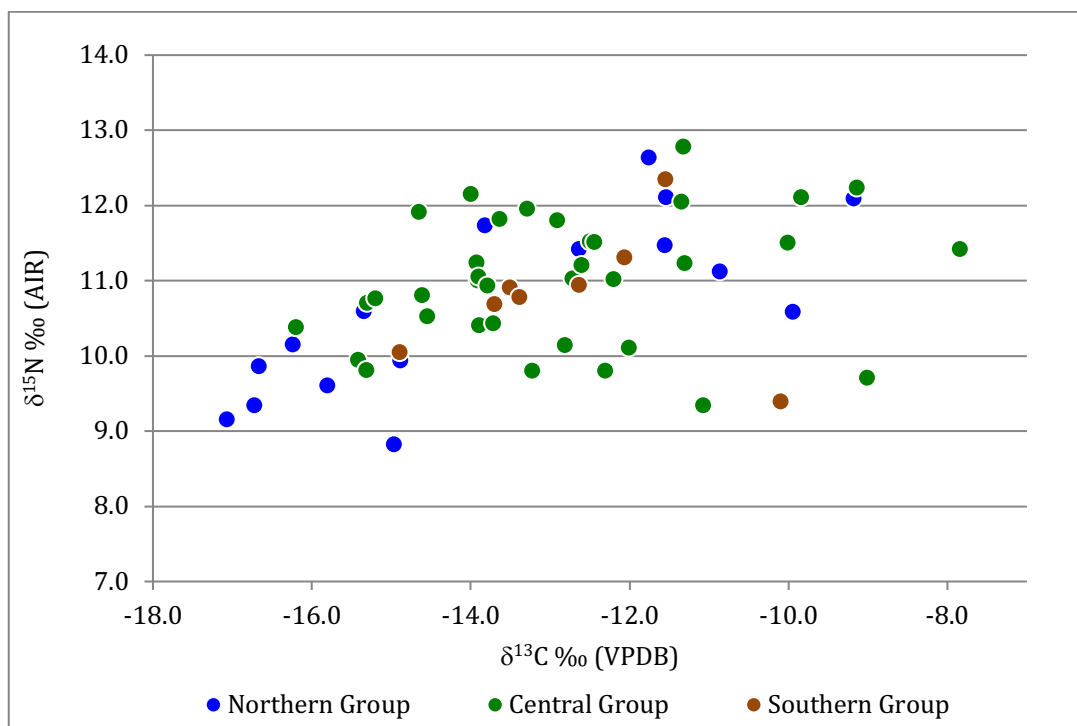


Figure 6. Human stable carbon and nitrogen results (excluding three infants/young children) from The Bahamas and TCI divided into northern, central and southern groups as defined in Figure 5.

While the fragmentary and incomplete nature of most of the skeletal material in the project limited sex estimation through traditional osteological methods, combining what results are available (e.g., Mack and Armelagos, 1992; Schaffer et al., 2012; RJS pers obs) with individuals whose sex was determined genetically (Fernandes et al., 2020) provides a sufficient sample size (12 females and 22 males) to at least provisionally explore the possibility of sex-based dietary differences. An unexpected finding was that males show significantly higher median  $\delta^{13}\text{C}$  values (-12.7‰ vs. -13.9‰, Mann-Whitney,  $Z = 2.13$ ,  $p = 0.033$ ) (Figure 7), while the difference in

$\delta^{15}\text{N}$  is only suggestive (11.2‰ vs. 10.7‰, Mann-Whitney,  $Z = 1.77$ ,  $p = 0.077$ ). There is substantial overlap in male and female  $\delta^{13}\text{C}$  values, but their medians differ by 1.2‰. This difference is large enough to be biologically meaningful and suggests that males consumed proportionately more marine foods and/or maize. A possible confounding factor is the diachronic trend to decreasing  $\delta^{13}\text{C}$  values; if, for whatever reason, more males featured in the earlier phases, then this, rather than sex, could be responsible for the observed pattern. When tested, there is no significant difference in the median dates of females and males (Mann-Whitney,  $Z = 0.95$ ,  $p = 0.340$ ). While the difference in  $\delta^{15}\text{N}$  is not statistically significant, the trend is in the expected direction for a greater contribution of marine resources, rather than of maize. Moreover, the presence of a small positive correlation between the two isotopes could justify the use of a one-sided test, the result of which would reject the null hypothesis. We note this only informally.

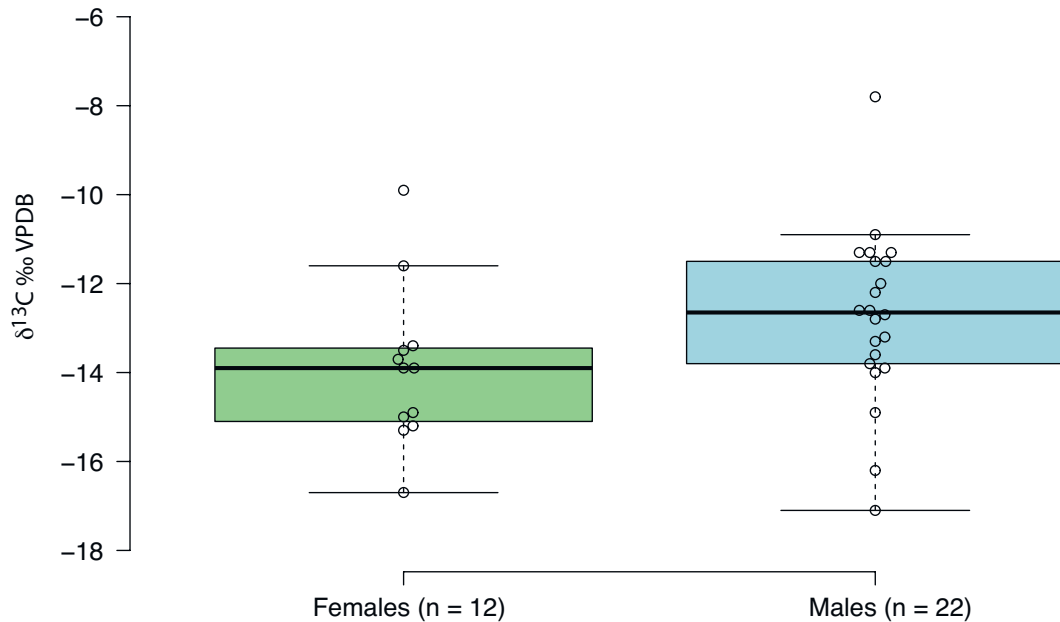


Figure 7. Boxplots comparing male and female  $\delta^{13}\text{C}$  values (Mann-Whitney,  $Z = 2.13$ ,  $p = 0.033$ ).

Using the median of the 95.4% probability intervals, there is a weak to moderate diachronic trend of decreasing  $\delta^{13}\text{C}$  values for both unmodeled and modeled dates, though it is slightly stronger in the former ( $r^2 = 0.185$  and  $0.131$ , respectively,  $p < 0.01$ ) (Figure 8). The distribution of the data suggests that a polynomial model provides a better fit ( $r^2 = 0.233$  and  $0.218$ , respectively,  $p < 0.001$ ), capturing greater variability after ca. AD 1400. It can be noted that a separate regression equation for the pre-1300 unmodeled and modeled median dates shows a stronger relationship ( $r^2 = 0.378$  and  $0.330$ , respectively,  $p < 0.001$ ). There is no corresponding decrease in  $\delta^{15}\text{N}$  values

using either unmodeled or modeled dates ( $r^2 = 0.042$  and  $0.040$ , respectively,  $p > 0.10$ ,  $n = 60$ ; Figure S4). That this trend is temporal rather than spatial is confirmed by the absence of any significant difference in  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values from the northern, central and southern island groups, as noted above.

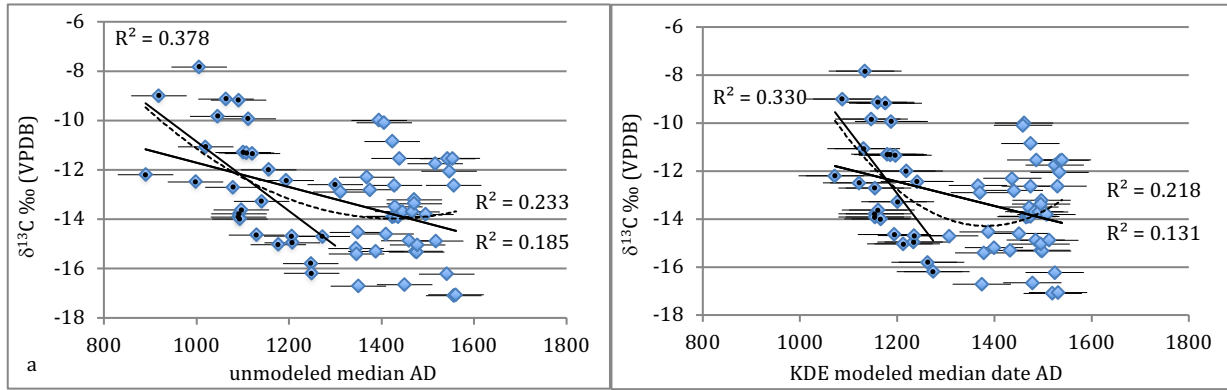


Figure 8. Relationship between a) unmodeled and b) KDE modeled median dates and  $\delta^{13}\text{C}$  values ( $n = 66$ ). A separate regression line is shown for median dates falling pre-1300 AD (infilled symbols). Error bars approximate a 68% confidence interval. A curvilinear regression model (2<sup>nd</sup> order polynomial) is also shown. All  $r^2$  values are statistically significant at  $p < 0.01$ .

### 3.3 Strontium isotope and elemental concentration results

The strontium isotope results average  $0.70921 \pm 0.00007$  ( $n = 17$ ) (Table S7). As the  $^{87}\text{Sr}/^{86}\text{Sr}$  results fail the Shapiro-Wilk test for normality, we use the median absolute deviation (MAD) to identify two outliers, both male as determined genetically (Fernandes et al. 2020): one (SBH2, 0.70935) being 6.4 MADs above the median, and the other (SBH5, 0.7090) 8.9 MADs below it. Both are from Sanctuary Blue Hole. Their removal results in a distribution that does not depart significantly from normality (cf. Wright, 2005), with an unchanged mean of  $0.70921 \pm 0.00003$ , consistent with that of late Quaternary limestone, modern seawater and modern plants on the islands (Faure et al. 1965; Schulting et al. 2018). Enamel strontium concentrations [Sr] are extremely high, averaging  $878 \pm 408$  ppm ( $n = 17$ ). While not markedly different, the [Sr] values associated with the two outliers do fall at the lower end of the range seen in the other ‘local’ results.

## 4. Discussion

The earliest and latest reservoir-corrected directly dated human remains in the Bahamian archipelago are AD 710–1015 and AD 1435–1670 (unmodeled) or AD 930–1160 and AD 1515–

1680 (modeled). The difference is particularly marked for the early dates, which have been constrained by the model. It must be emphasized that neither scenario represents the entire settlement history of the islands, but only the evidence for burial. Nevertheless, the early dates in both cases correspond well with what is currently understood to be a demographic expansion on the islands (Keegan, 1985; 1992) and with the onset of the Medieval Warm Period, suggesting a causative link (Figure 9). In the centuries prior to this, TCI in particular saw forays – perhaps seasonal, but with indications of longer-term settlement as well – from Hispaniola for the exploitation of certain marine resources, including conch and other shellfish, sea turtles and salt (Carlson, 1999; Keegan, 1992; Sinelli, 2010).

The more recent end of the range raises the possibility of continued presence of Lucayans on the islands well into the early seventeenth century. This is where the correction for ‘old carbon’ introduced through the consumption of marine foods becomes crucial. Without it, the modeled end date is *AD 1410–1485*, more consistent with the oft-cited date of 1520 for the depopulation of the islands (Sauer, 1966). The finality of this has been questioned for some time, based on occasional radiocarbon dates from settlement sites suggesting later activity (Berman et al., 2013; Blick and Dvoracek, 2011; Jones O’Day, 2002; Morsink 2015; Sinelli, 2010). Since no indigenous presence is expected on the islands after the second decade of the sixteenth century, this evidence has often been dismissed as reflecting disturbance and mixing of deposits; applying ‘chronometric hygiene’, many of these dates probably would be rejected (cf. Fitzpatrick, 2006). The results directly on human remains, however, are not so easily dismissed, and hint at the possibility of some continued Lucayan activity decades later than previously thought. It is likely that any remaining population would be small and dispersed (to the extent of being unsustainable) and extremely wary.

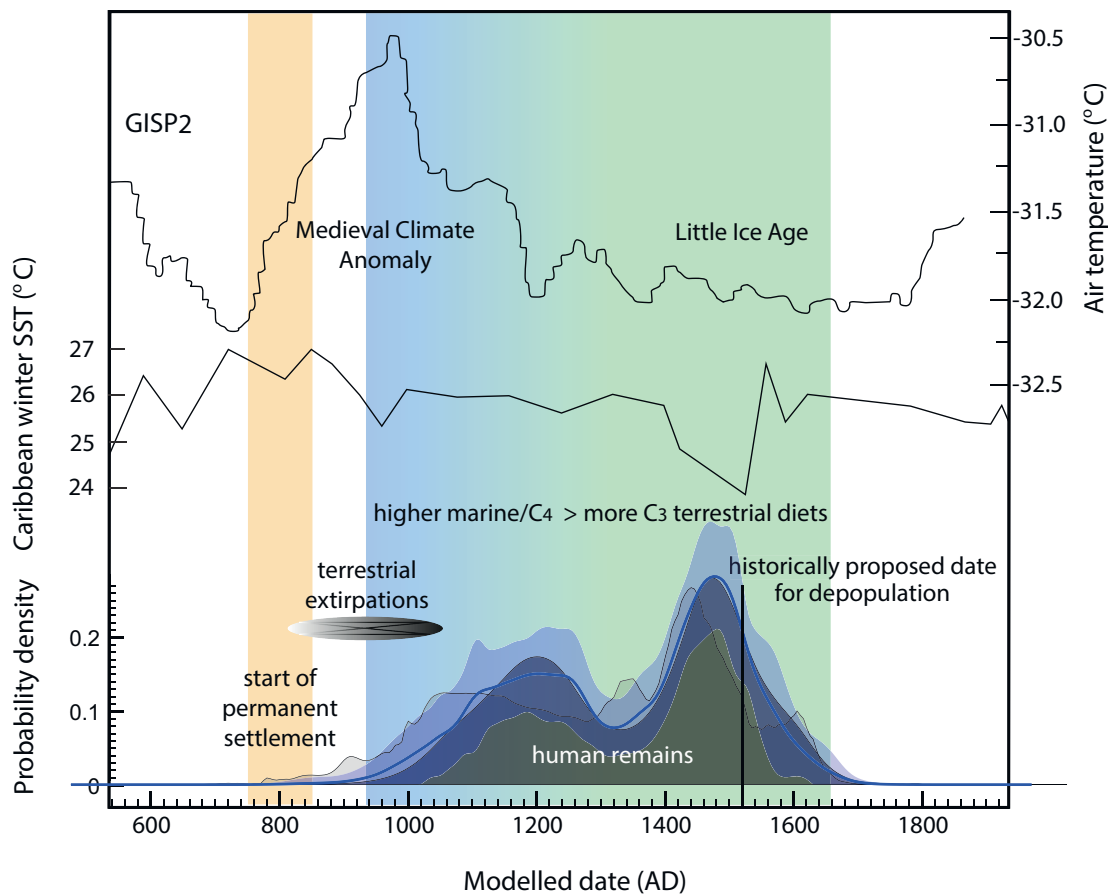


Figure 9. KDE plot of dates on human remains from The Bahamas/TCI shown with GISP2 ice core climate record (Alley, 2004) and Caribbean winter sea-surface temperature (Nyberg et al., 2002). See text for discussion of terrestrial extirpations. The dark gray distribution is the result of the KDE model. The blue line and blue bands mark  $\pm 1SD$  of the KDE distribution (Bronk Ramsey, 2017).

The observed decrease in  $\delta^{13}C$  values over time suggests a decline in the use of maize and/or marine resources over the ca. 550 (modeled) or 650 (unmodeled) years represented in our study. Analysis of vertebrate faunal assemblages from blue holes on Abaco indicate the presence of a viable terrestrial ecosystem, the larger members of which comprised large ground-dwelling birds, rock iguanas (*Cyclura carinata*), tortoises (*Chelonoidis* sp.), hutia (*Geocapromys ingrahami*), and, as the apex predator, the Cuban crocodile (*Crocodylus rhombifer*) (Hastings et al., 2014; Steadman et al., 2007). These species would have been highly vulnerable to human predation, and that the extinction or extirpation of a number of these and other species appears to have occurred not long after AD 1000 suggests that human colonists (and their dogs) did indeed play a role, typical to that seen in many other island contexts, both in the Caribbean and worldwide (Fitzpatrick and Keegan, 2007; Keegan, 2001). Small islands are particularly vulnerable to

overexploitation, since they tend to have lower species richness and greater difficulties in recruitment from larger hinterlands (MacArthur and Wilson, 1967). Based both on human stable isotope results and faunal assemblages, however, these terrestrial species appear to have played only a relatively minor role in early Lucayan diets. A possible exception is the hutia, a mid-sized rodent, bones of which have been found in considerable numbers on archaeological sites, including on TCI where the species does not naturally occur, strongly suggesting that they were introduced and managed by humans (LeFebvre et al., 2019a). Given that it is a prolific breeder, hutia could have been an important source of protein and fats, as well as another agent of landscape modification (Campbell et al., 1991).

There is no evidence for the concomitant decrease in  $\delta^{15}\text{N}$  values that would be expected with a decline in marine foods, which could implicate a decrease in the consumption of maize, present in The Bahamas from at least AD 800 (Berman and Pearsall, 2008; 2020), though to what extent it featured in diets is not known. As maize is relatively low in protein, it would have had a far smaller impact per unit weight on collagen  $\delta^{13}\text{C}$  values than high-protein marine fish and so would be underrepresented (Ambrose and Norr, 1993; Jim et al., 2006). That said, when a reliable source of carbohydrates is available, it typically forms a much larger part of human diets than protein-rich animal foods, and so maize (and root crops) would still be expected to feature in collagen stable isotope signals, as indeed is suggested by the low  $\delta^{13}\text{C}$  hydroxyproline value of -21.8‰ from Stargate vs. the bulk collagen  $\delta^{13}\text{C}$  value of -16.7‰. Nevertheless, as discussed below, the zooarchaeological evidence is consistent with a decline in the utilization of inshore marine resources. An alternative explanation involving a shift in the marine species being exploited (i.e., towards deeper water fishing away from the  $^{13}\text{C}$ - and  $^{15}\text{N}$ -depleted reefs) can be rejected based both on the paucity of deep-water fish remains in the zooarchaeological record (Newsom and Wing, 2004), and the absence of any increase in human  $\delta^{15}\text{N}$  values over time that would be expected with a shift to non-reef fishes.

Breaking down the trend century by century, it appears that the decrease in  $\delta^{13}\text{C}$  occurred early, within the first one or two centuries captured in our dataset (Figure 10). An ANOVA test ( $F = 5.11, p = 0.001$ ) with Bonferroni post-hoc correction shows a significant decrease between AD 1100–1200 and all subsequent centuries (excepting AD 1220–1300,  $p = 0.055$ ). Provisionally accepting that this is tracking an early decrease in the use of marine resources, the implications are that, in a classic ‘push’ or ‘pull’ scenario, either: 1) the highest ranked inshore marine resources were rapidly overexploited leading to a greater reliance on terrestrial resources; or 2)



the establishment of terrestrial C<sub>3</sub> crops made these more attractive leading to a relative decline in the use of marine resources and/or maize. It is perhaps difficult to envisage relatively small founder populations seriously impacting marine resources over only a few centuries (cf. Baisre 2010), but from the outset this was not just a subsistence economy: there is evidence that marine products from TCI were being processed, probably salted, and taken to Hispaniola (Morsink, 2013). Furthermore, the impacts may have been localised and limited to certain high-ranked marine species, but nevertheless sufficient to bring about a shift in decisions made regarding the balance of resource use.

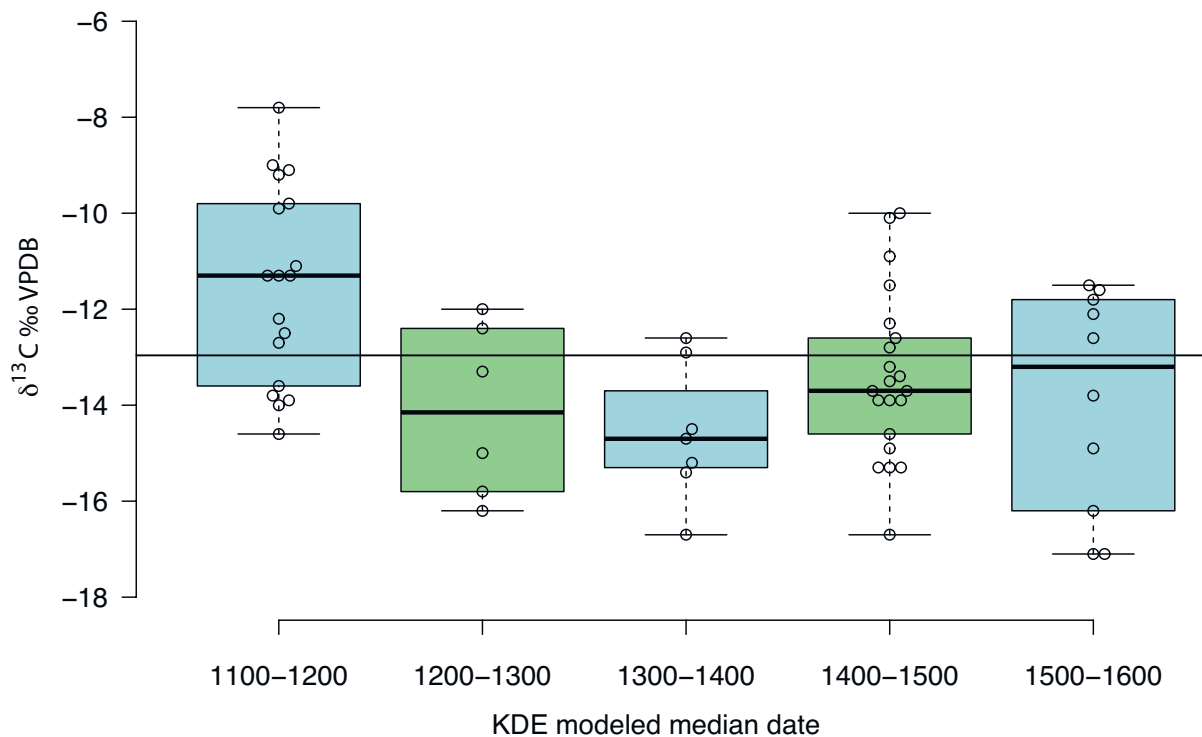


Figure 10. Boxplots showing  $\delta^{13}\text{C}$  values by KDE modeled median dates in one-century bins (the 1100–1200 bin includes two results in the last quarter of the eleventh century). The horizontal line shows the overall mean of 13.1‰.

Temporal changes in the genera represented in Lucayan faunal assemblages on San Salvador are consistent with overfishing of some reef fish, especially large predatory fish (Blick, 2007; 2012; Carlson, 1999; Carlson and Keegan 2004; see also Grouard, 2010; Pestle, 2013), though this trend lacks the time resolution now available for the human remains. Green (*Chelonia mydas*) and loggerhead (*Caretta caretta*) turtles would have been both easy prey and a highly ranked resource (Keegan, 1985), and there is evidence for the initial exploitation of nesting sites, leading to a sharp decline in the numbers of green turtle remains within the first century (AD 700–800) of



occupation at Coralie on Grand Turk (Carlson, 1999). Later sites on TCI show few turtle remains (Jones O'Day, 2002). Both green and loggerhead turtle remains also appear on early sites on San Salvador, with a decline in the latter over time possibly indicating their overexploitation (Blick et al., 2010). In the Caribbean, these species share similar isotopic values to those of reef fish (Vander Zanden et al., 2013) and so could be a contributing factor in the early decrease in human  $\delta^{13}\text{C}$  values. A decrease in  $\delta^{13}\text{C}$  values is also seen at Punta Candeleró, Puerto Rico, where it is argued to represent a shift from reliance on higher- to lower-trophic level fish over a period of six centuries (Pestle, 2013).

The 'pull' scenario must have involved a greater contribution from  $\text{C}_3$  crops and/or fauna. The high nitrogen requirements of  $\text{C}_4$  maize (Ciampitti and Vyn, 2012) would make it a challenging crop for long-term cultivation on The Bahamas and TCI, even given the initially greater soil fertility prior to the extensive deforestation of the historic period. In theory, fertilizers (e.g., kitchen refuse, seaweed, bat guano, night soil) could have been used to maintain soil fertility, and indeed this may have been essential to support any significant increase in the reliance on maize over time. But the trend we observe in the human  $\delta^{13}\text{C}$  results is one of a *decrease* in the relative contributions of both marine resources and maize – however much the latter featured – in favor of  $\text{C}_3$  crops, of which the most important would have been cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), yam (*Dioscorea trifida*) and zamia (*Zamia lucayana*). Direct evidence for their use from at least AD 800 has been found through starch grain analysis of processing tools from archaeological sites in The Bahamas and TCI (Berman and Pearsall, 2008; 2020; Ciafolo et al., 2018; 2019; 2020; Sullivan et al., 2019). The advantage of these root crops is their combination of high yields – higher caloric return per hectare than any cereal crop, including maize – and low nutrient requirements (Alves, 2002; Cock, 1982; Watlington, 2003). They do require a certain soil depth, but this would be available on sandy beaches and dunes and in the many solution holes ('banana holes') that dot the islands (Figueredo, 2015). Artificial garden mounds could easily have been created, akin to the *conucos* or *montones* documented by early Spanish *chronistas* for the Taíno of Hispaniola (Oviedo, 1959 [1536]), as well as being attested on The Bahamas in the historic period (Craton and Saunders, 1999). Indeed, it has recently been argued that the sediments of the Minnis-Ward site (SS-3) on San Salvador provide evidence for the presence of deep (ca. 1 m) anthropogenic soils akin to the Amazon Basin's *terra preta* or 'black earth' (Blick and Kjellmark, 2017). Anthropogenically-altered soils that might indicate horticultural plots have also been identified on sites on TCI (Roth, 2002; Sullivan et al., 2019).

Potentially more problematic is cassava's greater susceptibility to low temperatures and drought. Yields are greatly reduced with cooler temperatures (less than 20 °C during the six months required for a cassava crop) and low rainfall, less than 500 mm annually (Alves, 2002; Keating and Evenson, 1979). The former could be a factor in the northern Bahamas, while the latter would be an issue in the drier islands of the southern Bahamas and TCI. Both climatic factors would be exacerbated during the onset of the LIA, affecting the circum-Caribbean from ca. AD 1400 (Hodell et al., 1991; 2005). Nevertheless, we see no significant differences in either  $\delta^{13}\text{C}$  or  $\delta^{15}\text{N}$  values between island groups from north to south, nor do we see any shift corresponding to the LIA (Figures S6–S10). A potentially relevant factor here may be an increase in marine productivity caused by lower sea-surface temperatures in the LIA (Nyberg et al., 2002), a relationship that is well attested through modern studies of the impact of global warming on reef communities in the circum-Caribbean (Jury, 2011; Maharaj et al., 2018; Riegl et al., 2003). This may have made marine resources more attractive, mitigating the greater uncertainty of crop yields. While the sample size is too small to confirm this statistically, it is interesting to note a possible rebound in the use of marine resources by some communities post-1400 during a period showing marked reduction in Caribbean winter SST (Figures 8, 9).

It is likely that the contribution of high-protein marine resources would essentially override the subtler distinctions that we might otherwise see in the consumption of low-protein  $\text{C}_3$  and  $\text{C}_4$  crops not only post-AD 1400, but throughout the occupation of the archipelago, particularly post-AD 1200. The protein content of cassava is particularly low (Lancaster et al., 1982), so that its contribution to  $\delta^{13}\text{C}$  measurements on bone collagen will be significantly underrepresented, since dietary protein is preferentially routed directly to consumer tissue protein (Ambrose and Norr, 1993; Jim et al., 2006). The implication of this is that the observed trend in  $\delta^{13}\text{C}$  values may only be hinting at the size of the shift towards terrestrial  $\text{C}_3$  resources after ca. AD 1200. This will be addressed in future work through the measurement of  $\delta^{13}\text{C}$  on dental enamel, and the use of other isotope systems and single amino acids.

Lastly, tooth enamel from a subset of individuals was analyzed for  $^{87}\text{Sr}/^{86}\text{Sr}$  and [Sr] as part of a pilot study. When corrected for the MRE, all of the 17 individuals represented post-date AD 1000, when permanent settlement of the islands is attested, and therefore we would not expect to find evidence for the presence of early colonists. What was not clear, however, was the extent to which individuals continued to move between Hispaniola and Cuba (more distant islands being less likely) and the islands of the Bahamian archipelago. Early Spanish *chronista* accounts, for

example, refer to a Lucayan man named *Caonabó* becoming one of five paramount *caciques*, or chiefs, on Hispaniola (Colón 1992 [1571]; Keegan, 2008). Material exchanges with the neighboring large islands are also attested in the presence of hard stone artifacts on Bahamian and TCI sites (Berman, 2011; Keegan, 1992; Sinelli, 2010; 2013). An aspect of Lucayan adaptation to their challenging environment was no doubt the maintenance of ties (e.g., marriage and exchange relations) with communities on the Greater Antilles, providing a social and economic buffer and imparting significantly greater resilience to the socioeconomic system (Adger, 2000; Walker et al., 2004). This may have been particularly important for communities in the more arid southern island group, given their more precarious climate for horticulture (Sinelli 2010).

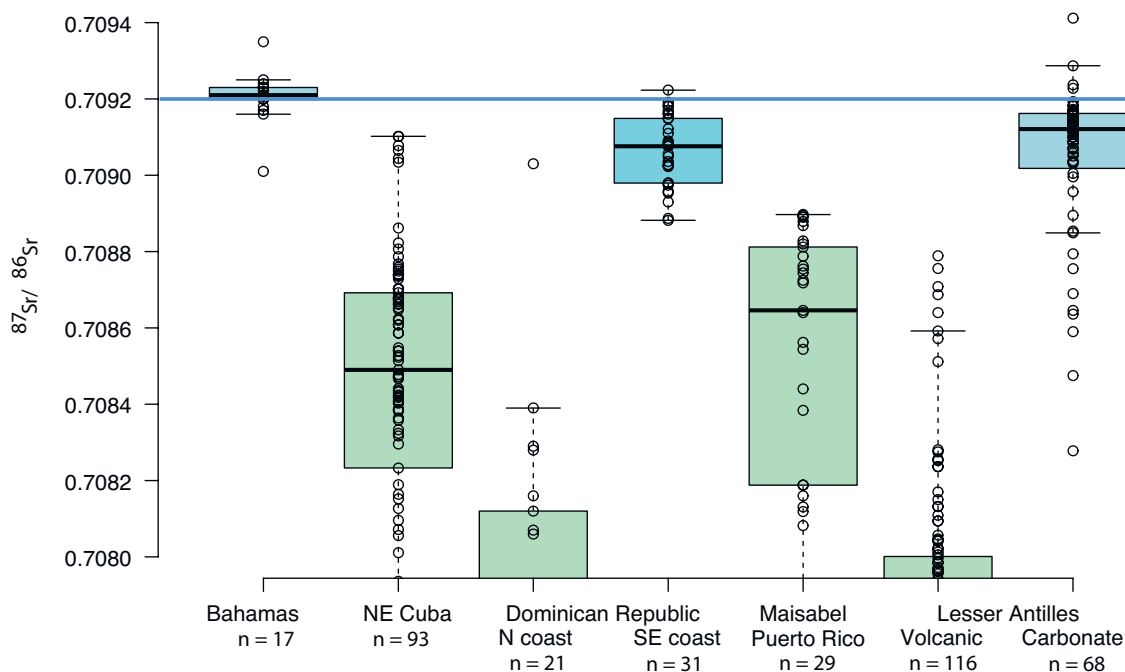


Figure 11. Boxplots comparing Bahamian  $^{87}\text{Sr}/^{86}\text{Sr}$  results with comparative datasets from other Caribbean islands (Laffoon, 2012; Shev, 2018). An extreme outlier of 0.7109 from NE Cuba is not shown. The north coast of the Dominican Republic includes dogs and humans; all other groups are humans only. The horizontal line at 0.7092 represents both modern seawater and the mean value of modern plants ( $n = 91$ ) from the Bahamian archipelago (Schulting et al., 2018).

The biologically available  $^{87}\text{Sr}/^{86}\text{Sr}$  value baseline for the late Quaternary limestone islands of the Bahamian archipelago is very well characterized as ca. 0.7092, matching that of modern seawater (Schulting et al., 2018). Fifteen of the 17 human values exhibit this value and hence are consistent with a local origin. What is less clear is the extent to which individuals with this value could also be found on Cuba and Hispaniola; if common, the resulting equifinality would

undermine the method's usefulness in this context. Reefs surround much of Cuba and Hispaniola, backed by Quaternary carbonate limestone coastal platforms, though along their north coasts this coastal strip is generally quite narrow, and is in turn backed by either older post-Eocene limestones or volcanic geologies (French and Schenk, 2004). Consuming either marine foods and/or plants grown on Late Quaternary limestone would result in  $^{87}\text{Sr}/^{86}\text{Sr}$  values of ca. 0.7092, while foods grown on less radiogenic post-Eocene limestones and volcanic geologies would present lower values.

While limited comparative data are available, it can be noted that the results for a large number of humans from the Late Ceramic Age (AD 600-1492) to Colonial Period (post-AD 1492) site of Chorro de Maíta on Cuba's north coast are considerably less radiogenic than 0.7092 (excepting an extreme outlier of 0.7109, suggested to be a first generation African slave from the early historic period) (Valcárcel Roja et al., 2011) (Figure 11).  $^{87}\text{Sr}/^{86}\text{Sr}$  values for dogs and humans from pre-Columbian sites near the north coast of the Dominican Republic are even less radiogenic (Shev, 2018), and, while humans from sites along the island's southeast coast exhibit higher values (Laffoon, 2012), they are still distinguishable from the Bahamian results. A possible exception requiring further research would involve communities on the Quaternary limestone islands of the Jardines del Rey off Cuba's north-central coast, concerning which little is currently known (Cooper, 2007). Thus, at present the  $^{87}\text{Sr}/^{86}\text{Sr}$  values of The Bahamas appear quite distinctive, provisionally supporting the interpretation that individuals with values of ca. 0.7092 are indeed local to the archipelago. The Late Ceramic Age communities of the islands of the Greater Antilles were much more heavily focused on horticulture than on fishing – as supported by the available stable isotope data (Buhay et al., 2013; Laffoon et al., 2020; Shev, 2018; Stokes, 1998) – and it is likely that fields were preferentially located on older, more eroded limestone rather than the karstic Quaternary limestone, or, where available, on richer volcanic soils, both with less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values (Bataille et al., 2012; Laffoon et al., 2012).

This leaves two individuals who must have spent at least part of their childhood outside The Bahamas/TCI. Both are adult males from Sanctuary Blue Hole on Andros, but one is lower (0.7090) and the other is higher (0.7094), indicating that they did not share a common origin. Given their more varied geologies, bioavailable  $^{87}\text{Sr}/^{86}\text{Sr}$  values above and below 0.7092 can be found on both Hispaniola and Cuba (Bataille et al., 2012). That said, SBH2's value of 0.7094 is unmatched in 173 measurements on humans and dogs from the Greater Antilles, with the only comparable reported values coming from the Lesser Antilles – where they are also outliers

(Figure 11) – and from Trinidad (Laffoon, 2012; Ostapkowicz et al., 2017). In contrast, the value of 0.7090 for SBH5 can be matched in Cuba and Hispaniola and many other locations in the circum-Caribbean (Laffoon et al. 2017).

## 5. Conclusions

This study has demonstrated the utility of a combined program of radiocarbon dating and stable isotope analysis in order to address questions of past human island adaptations. It is because of a robust chronological framework that we were able to document previously unknown dietary trends over six centuries of pre-Columbian inhabitation of the Bahamian archipelago, most plausibly interpreted as a declining use of marine resources due to a rapid, localized over-exploitation of near-shore reef fisheries. Yet the Lucayan populations of the islands were resilient, and able to compensate apparently through an increased reliance on terrestrial root crops, and perhaps the management of hutia. The identification of sex-based differences in diets is a novel contribution to our understanding of pre-Columbian Caribbean societies, and will no doubt stimulate further research. In the same vein, the results of a pilot study using strontium isotope analysis suggests that, while still a concern, equifinality may be less of an issue in The Bahamas and TCI than previously thought, permitting the investigation of individual mobility between the archipelago and the Greater Antilles, or potentially even further afield. We have identified the first two such migrants. Yet the majority of individuals analyzed are consistent with an origin within the archipelago, emphasizing the success of Lucayan adaptations to a challenging environment.

## 6. CRediT statement

**Rick J Schulting**: conceptualization, methodology, formal analysis, writing (original draft), funding acquisition, supervision; **Christophe Snoeck**: investigation, funding acquisition; **John Pouncett**: investigation, visualization; **Fiona Brock**: investigation, writing (review and editing); **Christopher Bronk Ramsey**: software, methodology; **Thomas Higham**: investigation, resources, writing (review and editing); **Thibaut Devière**: investigation; **Kelly Delancy**: writing (review and editing); **Michael Pateman**: writing (review and editing); **William Keegan**: writing (review and editing); **Joanna Ostapkowicz**: conceptualization, writing (original draft), funding acquisition

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