UNIVERSITY OF CALIFORNIA SAN DIEGO

800-1000 CE, an era of cultural and climate changes in the Indigenous Caribbean Societies

A Dissertation submitted in partial satisfaction of the requirements
for the degree of Doctor of Philosophy

in

Anthropology

by

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The Dissertation of Mariela Declet Pérez is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

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DEDICATION

To my ancestors, my family, and the community, this is a way of paying respect to all of you, who I am, and where I come from. The road to get here has been hard, but you have never doubted me, and for that, I am eternally grateful. To all of you who have been part of this journey and allowed showing what I am capable of, this is for you.

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FIELD OF STUDY

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Studies in Environmental and Marine Archaeology

ABSTRACT OF THE DISSERTATION

800-1000 CE, an era of cultural and climate changes in the Indigenous Caribbean Societies

by

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As climate change occurs rapidly, communities affected by it are desperately seeking answers and hope for the future. They face questions about how it will look, how the marine ecosystem will resist, and how we can adapt. This dissertation examines past examples in the Caribbean, especially in Puerto Rico, where indigenous societies faced changes similar to the present to answer some of the current communities' questions. Even though contemporary and past societies may not be directly comparable, the deep historical and time perspective used in archaeology can provide valuable data to present problems. By using the Anthroposystem/ Socio-ecological framework, it was possible to organize the data in the abiotic, biotic, and

cultural contexts with an awareness of scales, and produce data to examine the impact of climate change and sudden atmospheric events on their environments and the associated subsistence and residential practices of coastal societies in the Caribbean (Puerto Rico) whose marine ecosystems represent their primary source of food or economy. As a result, it was possible to identify the effects of the Medieval Climate Anomaly around 900-1000 CE on the Caribbean and how the coral reef could have been affected. Additionally, it was possible to identify fishing traditions that helped conserve the fish communities near the archaeological sites. The research presents important results for the island of Puerto Rico and the coral restoration projects in the area by helping identify a coral reef zone that can be categorized as sentinel containing a possible genetic variation resistant to coral bleaching. Identifying these zones will provide base models for restoration projects and long-term utilization to ensure the communities' security of fishing banks in the region.

INTRODUCTION

Global change is taking place rapidly, transforming climate patterns and triggering record-breaking atmospheric events faster than long-term Holocene trends (Gupta & Tiwari, 2021; Kaniewski et al., 2020; Medley et al., 2018). The magnitude and frequency of climatic fluctuation can exert tremendous societal and environmental stress over impacted areas (Cooperm, 2013; Field et al., 2014; Masson-Delmotte et al.,2018; McCloskey & Knowles, 2009; Poortliet et al., 2020). Changing climatic parameters can drive natural disasters, droughts, water scarcity, flood risks, heat stress, poverty, famine, food and nutritional insecurity, and global health problems (Douglass & Cooper, 2020; Poortvliet et al., 2020; Thomas et al., 2019; ICOMOS, 2019; Zandalinas et al., 2021). An increasing number of people and properties have been affected by catastrophic events in the very recent past. As these events continue to increase in intensity and damage, the need for disaster and loss prevention and mitigation (Zakour & Swager, 2018; Glasser, 2020), as well as the need for climate scientists to understand the social roots of vulnerability (Huang et al., 2020; Thomas et al.,2019; Sarkodie & Strezov, 2019) have become more urgent.

Climate change has been defined as a change in the state of the climate that can be identified by fluctations in the mean and/or variability of properties and persists for an extended period of time, usually decades or more (IPCC,2007; Aish, 2020). No single phenomenon can be pinpointed as climate change; instead, it is experienced as a series of abnormal and unexpected weather events that push the average beyond the existing record. Unexpected, high-magnitude events can make changing climatic parameters particularly hazardous for human societies: the experienced drivers and atmospheric phenomena fall beyond the predictable range for which societies have prepared. As climate change accelerates, these impactful and unprecedented

events, due to their more significant frequency and unpredictability, negatively impact societies in which a series of economic, social, and political events are already occurring and affecting their stability (Thomas et al., 2019; Zakour & Swager, 2018). The drivers of climate change can affect social vulnerability by destabilizing the ecological bases of livelihood security (ICOMOS, 2019; Jorgenson et al., 2019).

This proposition holds significant relevance within the discourse on climate change, as the subsistence practices governing dietary choices and the selection of habitats are intricately intertwined with individual and collective identities (Rivera-Collazo, 2021). The Anthroposystem complex, or socio-ecosystem Figure I. 1; modified from (Grouard, 2023), is considered a structural and functional entity of society-environment interactions (Lévêque et al., 2003). The anthroposystem is an "interactive system between two groups consisting of one or more socio-systems, one or more natural or artificial ecosystems, within a given geographical area, that evolve over time under the effect of external or internal factors. As such, the anthroposystem has certain characteristics that define it as a structural or functional entity of society-environment interactions, a complex, hybrid, and open system comprising different levels of organization that are interwoven, secant or adjacent, taking place in a local, regional (like workshop zones) or global space, and evolving over time, which implies, among other things, that it represents an inherited social construction: natural, anthropic and institutional legacies" (Levêque et al., 2003).

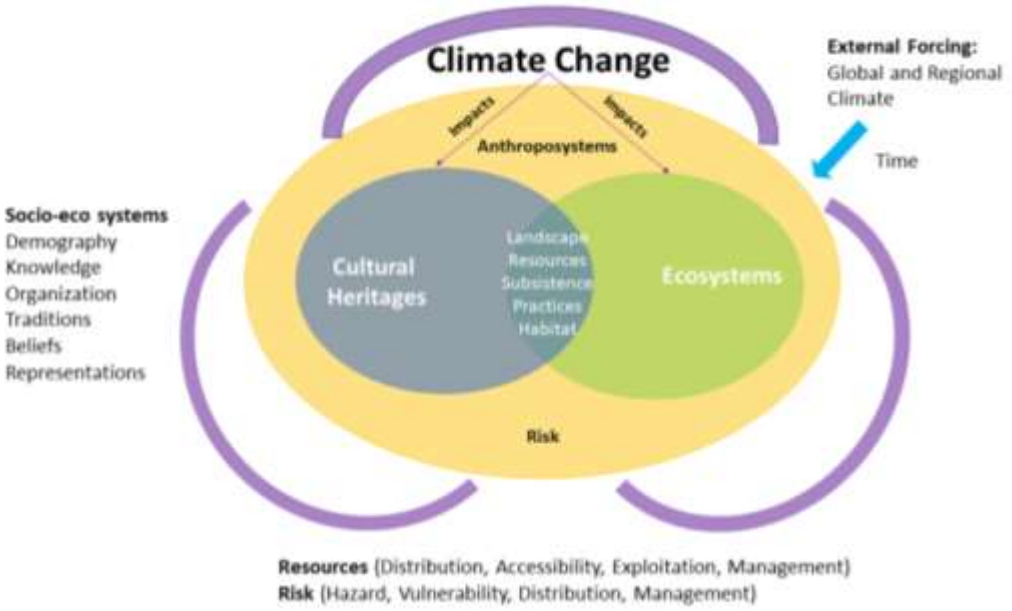

Figure I. 1: An Anthropoposystem or socio-ecosystem complex model illustrates systems' interaction and how climate change impacts them—modified from Grouard, 2023.

These interactions are analyzed primarily from the standpoint of resources and risks. Water resources, subsistence, and geomaterials (distribution, accessibility, exploitation, management) are material and symbolic activities. The environmental risks (hazards and vulnerabilities, distribution, management) are essentially linked to resources, with regard to the variability of social demand, the carrying capacity of the environment, and climatic variability (drought, flooding, erosion, loss of soil and seabed fertility, overexploitation of land and sea, deforestation). The mobilization of the anthroposystem concept also enables us to study the geographical environment, defined by George (1970) as "the natural or developed space surrounding a human group, on which it acts, and whose climatic, biological, edaphic, psycho-sociological, economic, political, etc., constraints affect the behavior and state of this group" and the ecosystem of the territory of subsistence. The latter is understood as the areas usually used for the daily subsistence of the population, according to the definition of " *site exploitation*

territories" used in " *site catchment analysis* " (Bailey, 2005). The dynamics of the socio-ecosystem are linked to interactions within it, but also with other socio-ecosystems and climate and global change (Castanet *et al.*, 2021).These dynamics are deeply rooted in traditional knowledge, registered in history, deposited in archaeological sites, and modulated by colonialism and other historical processes (Wallman et al., 2018; Rivera-Collazo, 2021, 2022). Our modern ways of providing food and securing habitat are, in turn, affected by these historical processes, making it difficult to some extent to maintain or protect cultural heritage in the face of the current pace of accelerating climate change (Lewis & Maslin, 2015; Palsson et al., 2013; Rivera-Collazo, 2021).

It has been argued that archaeological research can contribute to the climate change discussion by providing examples of past societies' effective or ineffective response mechanisms and disaster management strategies (Haldon et al., 2018; Jorgenson et al., 2019; Peregrine, 2018; Rivera-Collazo, 2022). Archaeology has the potential to broaden our comprehension of long-term socio-environmental systems by fostering deeper integration between scientific inquiry and broader societal demands, as well as local spatial insights, all within the framework of sustainability (Rockman & Hritz, 2020).

Even though contemporary and past societies may not be directly comparable, the deep historical perspective used in archaeology can provide valuable data for present and future scenarios of risk reduction measures (Riede, 2017; Jackson et al., 2018, p. 61), including in island contexts (Wing & Wing 1995, 2001, Grouard et al. 2019; Rivera-Collazo & Perdikaris, 2023). Our ancient ways of food and habitat in the context of changing climates can help us identify different scenarios and alternate response strategies.

This research's central question is how changing climate and atmospheric events impact socioenvironmental dynamics that influence how people make sense of change. At the same time, this investigation explores how archaeology can contribute to our present knowledge of climate change management. To this end, a framework is presented to couple archaeological, environmental, and climate data, consider how vulnerabilities develop across different spatial and socio-cultural contexts, and assess how the reconstruction of social response to climate impacts can contribute to issues in the present.

Conceptual foundations

An 'event' refers to the onset of a fast-onset hazard, which entails the release of large amounts of energy that can cause destruction to the natural and built environment and cause traumatic injuries to people (Lindell & Perry, 2004). High-magnitude events – and their accumulation through time as climatic or environmental change – can become disasters when they coincide in space and time with human societies. Not all human communities are equally affected by high-magnitude events or climatic/environmental change; their process of making sense of them must be considered under historical, social, and traditional conditions within their lived places and times. How people make sense of the world is a multidimensional process interacting with natural and social dynamics from micro-local to global scales (Chimi et al., 2022; Dietz et al., 2020; Thomas et al., 2019).

Data from multiple sciences such as sedimentology, lithology, hydrology, geography, oceanography, and climate sciences can contribute to the understanding of exposure by identifying physical risks and hazards tied to specific locations and instants in time (Degroot et al., 2021; Rivera-Collazo, 2022). In addition to the disciplines mentioned, other areas of archaeology can also play a crucial role in understanding exposure to physical risks and hazards.

These include geoarchaeology, landscape archaeology, archaeobotany, and, of course, archaeozoology. These disciplines enable us to understand human interactions and their past environments, assess environmental change, and examine large-scale spatial patterns to identify land-use patterns and associated risks. In this way, archaeology can provide a holistic perspective on past societies' environmental risks and hazards, which can have important implications for contemporary risk management. In addition, multiple social sciences can help to understand the nuances of exposure, sensitivity, and adaptive capacity.

The vulnerability within a social group is influenced by 1) its ability to access knowledge (traditional or otherwise) to make sense of physical or social hazards, 2) its ability to develop adaptation or mitigation strategies, 3) its access to resources, 4) the role of governance over their capacity to identify, act on, and mitigate hazards (Peregrine, 2017); and 5) their socially acceptable cultural behaviors. All these factors are historically contingent. Access to resources, governance, culture, and knowledge are interwoven, interdependent, and affect each other, just as exposure, sensitivity, and adaptive capacity (Thomas et al., 2019). Studying these factors in ancient societies requires an interdisciplinary framework for analyzing and understanding how social differences cause uneven or differential vulnerabilities (Douglass & Cooper, 2020; Thomas et al., 2019; Rivera-Collazo, 2022).

The archaeological record is the physical accumulation of the material remains of social behavior, presenting a structuration of evidence produced by social and environmental processes at multiple temporal and spatial scales (Rivera-Collazo et al., 2018; Butzer, 1982; Bailey, 2007). The combination of these variables complicates the understanding of socio-ecological dynamics and social vulnerability, particularly the identification and decoding of events and processes that occurred in the past (Bailey, 2007; Burke et al., 2021; Zarza et al., 2023). Therefore,

archaeological research seeking to understand human response to climate change must apply theoretical and methodological frameworks consistent with relevant temporal and spatial scales to identify connected patterns (Rivera-Collazo et al., 2018; Silva et al., 2022). By carefully observing these processes, it is possible to avoid oversimplified conclusions that force the articulation of spatially or temporally incompatible data ("wiggle matching") or the interpretation of coincidence as causation (Rivera-Collazo et al., 2018; Silva et al., 2022).

Table I. 1 Scale- aware organization of the data. Modified from Rivera-Collazo et al., 2018.

Scale **Space/time**	**Small** Location/communities Generations (<100yrs)	**Medium** Line/Traditions (Centuries)	**Large** Basin/Cultures (Thousands of years)
Culture	Household Construction methods Subsistence acquisition Food insecurity Nutritional insecurity Demography Mobility	Settlement patterns Subsistence strategies Exploitation practices Global Health Technic systems Knowledge Social organization Exchanges Migrations	Culture changes Habitat changes Traditions Beliefs Representations Parenthood Exchanges Migrations
Biotic	Resource distribution Biome changes Ecosystem recovery Local climate conditions effects	Ecosystem coverage Ecosystem Security Irrigation system / flood drainage system Meso-scale climate conditions effects	Changes in biodiversity Regional to global ecosystem effects
Abiotic	Land-form, droughts, heat stress, flood risks, water scarcity, hurricanes, tectonic effects Characteristics of local climate conditions	Erosional processes, sea level rise, hurricanes development, tectonic instability Meso-scale climate conditions	Landscape change, sea level rise, landscape fragmentation, sea current changes, Regional to global climate conditions

To explore socio-ecosystem dynamics, we propose focusing on the physical or climate characteristics of the study area (abiotic factors), the biocenose context (biotic factors), and the

characteristics of the societies inhabiting that place (Culture) delimited by time and space (Table I. 1) (Rivera-Collazo et al., 2018).

We can evaluate or understand a Society's vulnerability, resilience, and adaptive capacity when we look at the three contexts as a system of interconnected sphere variables (Figure I. 2; modified from Grouard (2023), referred to as the socio-ecosystem framework and presents data on equal temporal and spatial scales, as suggested.

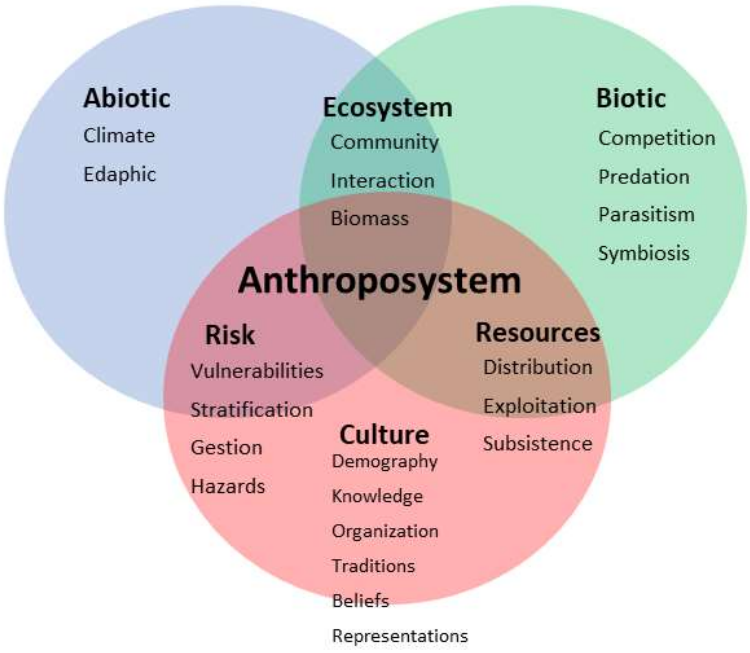

Figure I. 2 This is a model of the data and proxies' organization using the Anthroposystem or socio-ecosystem framework. The overlap of the three circles represents the interconnection between the abiotic, biotic, and culture variables, which provides a scenario to evaluate the vulnerability and resilience of societies impacted by climate change and atmospheric events, modified from Grouard, 2023.

Environmental and social processes at different time intervals and specific geographic locations are documented within the archaeological record, marine sediments, peat, speleothems, and ice and sediments cores (Burke et al., 2021; Sandweiss et al., 2020). While some may

represent timeframes of months, years, decades, or centuries, others may represent single episodic events (Sandweiss et al., 2020). Well-dated archaeological sequences can provide a robust record of climate change on local to regional scales and potentially identify past atmospheric/climate events at smaller scales (Burke et al., 2021; Jaffe et al., 2021; Rivera-Collazo, 2022; Sandweiss et al., 2020). Accurate research on human response to climate change requires the construction of high-resolution absolute chronological frameworks of both environmental and cultural data. Precise data sets support reconstructing past events and identifying how past societies experienced and responded to them.

Human decision-making should be analyzed using scale- and subject-appropriate social theories. To understand how people make sense of change and how they respond or adapt to it in the long term, it is necessary to consider the traditional social parameters **before** the event (memory), the characteristics **during** the event (impact), and what happened **after** the event (recovery and rehabilitation) (Rivera- Collazo, 2022). A return to conditions in which society finds new or similar stability prior to the event points to the strength of the social system and must consider how long it takes to recover (Rivera-Collazo, 2022) . Studying the distribution of settlements will provide clues related to exposure and residential security.

Examining food remains provides a sample of the ecosystems within the home range and the availability of traditionally sought-after prey, supporting the assessment of sensitivity and food security. Studying the broader assemblage of cultural practices will shed light on other elements relevant to understanding social vulnerability, such as traditions limiting or constraining adaptive capacity. Establishing the recurrence of events of similar type and magnitude could also hint at the existence of traditional knowledge about the phenomenon and how to respond to it (memory), the role of governance in controlling or supporting the society members, and their

access to resources to mitigate damages. The combination of these variables taps into an understanding of the role of traditional knowledge in human response to environmental change and the role of social resilience in recovery.

To test the socio-ecological framework, this research focused on the site of Tierras Nuevas, Manatí, and organized the evidence in abiotic, biotic, and cultural components to examine the impact of climate change and sudden atmospheric events on their environments and the associated subsistence and residential practices of coastal societies in the Caribbean (Puerto Rico) whose marine ecosystems represent their primary source of food or economy.

Paper/Chapter order:

Abiotic

The Medieval Climate Anomaly: A Crucial Period for the Caribbean's Pre-Columbian Societies (800-1300 CE)

Declet-Perez, Mariela, Grouard, Sandrine, and Rivera-Collazo, Isabel

This paper performs a literary review of the paleoclimate data available for the Caribbean region. It presents examples of archaeological sites affected by the changing climate and flood events related to hurricanes during the 800-1300 CE.

Biotic

Reconstructing Late-Holocene Climate and Human Interactions Effect on Coral Reef in Puerto Rico.

Declet-Perez, Mariela; Rodriguez-Delgado, Eric; Moulton, Melissa; Krumhardt, Kristine; Rivera-Collazo, Isabel

This paper proposes a palaeoecological reconstruction of past coral reef ecosystems on the central northern and southern coasts used by the indigenous people. The coral assessment presented the decline/absence of coral fragments around 800-1150 CE. Paleoclimate models were created to investigate this observation and assess if the climate conditions during 800-1300 CE were favorable to generate a decline in this marine ecosystem.

Cultural

Sustainable and Local Traditional Fishing knowledge: a New Case from Manatuabón Valley, Puerto Rico

Declet Perez, Mariela and Grouard, Sandrine

This paper analyses the Ichthyofaunal assemblage of Tierras Nuevas and Angostura, both sites located in the Manatuabón Valley. These sites present a unique opportunity for Puerto Rico to study the long-term uses of the central northern coastal marine resources and if the changing climate conditions affected the fish population from the Archaic period to the Late Ceramic Period. The result obtained from the analysis provides insight into the fishing tradition and traditional knowledge transmission between cultures.

Conclusion

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Chapter 1 The Medieval Climate Anomaly: A Crucial Period for the Caribbean's Pre-Columbian Societies (800-1300 CE)

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Introduction

Pre-Columbian Caribbean societies, particularly those in coastal areas, relied heavily on fish and shellfish as their primary animal protein source (Giovas, 2013, 2016, 2018; Grouard et al., 2019; Newsom & Wing, 2004; Wing, 2001; Wing & Wing, 2001). During the Early Ceramic Age (ECA)(600- 900 AD) and Late Ceramic Age (LCA) (900-1500 AD) occupations of Puerto Rico and other islands in the northeastern Caribbean Archipelago, significant cultural changes occurred that transformed the region. One of the most notable changes was in the diet, which presents a diversification of resources from marine ecosystems and increased integration of inland protein sources (Carlson & Keegan, 2004; Fitzpatrick & Keegan, 2007; Newsom & Wing, 2004; Wing, 1991, 2001; Wing & Wing, 2001). Zooarchaeological analyses also revealed a decline in the average size of certain species and a broadening of prey trophic levels during the late occupation period (Pestle, 2013). Some researchers have interpreted these dietary changes as a result of resource overexploitation (Carlson & Keegan, 2004; Fitzpatrick & Keegan, 2007; Giovas, 2013; Giovas et al., 2013; Giovas, 2016, 2018; Newsom & Wing, 2004; Pestle, 2013; Wing, 1991; Wing & Wing, 2001), while others have suggested a possible link to climate change or atmospheric phenomena (Cooper, 2012; Cooper & Peros, 2010; Giovas, 2018, 2021; Rodríguez Ramos, 2010; Rivera-Collazo & Perdikaris, 2023). However, the potential effects of

climate change and atmospheric events on marine ecosystems in this context have not been extensively explored. Only a few recent studies, such as Rivera- Collazo & Perdikaris, 2023 and Giovas 2021, have begun investigating past climate conditions as potential causes of marine ecosystem destabilization.

To better understand whether climatic conditions influenced cultural changes in the Caribbean, we have conducted a literary review of paleoclimate work in the region. The available data allowed us to describe the climate conditions from 400 CE to the present. The organization of the data helped delimit the climate conditions before, during, and after 900-1000 CE when the proposed change in diet at the circumcaribbean level was marked.

Background

Regional studies in the Caribbean have identified clear patterns in climate changes locally and regionally (Donnelly et al., 2015; Donnelly & Woodruff, 2007; Gischelr et al., 2008; Malaizé et al., 2011). Large-scale events such as North/South movements of the Intertropical Convergence Zone (ITCZ) (Haug et al., 2001), the North Atlantic Oscillation (NAO) (Black et al., 2007), and El Niño Southern Oscillation (ENSO) (Handoh et al., 2006) can have profound effects on precipitations, wind patterns, and hurricane development in the Caribbean. Studies of proxy indicators for past changes in sea surface salinity (SSS) and sea surface temperatures (SST) highlight the regional signature of these broader changes in North Atlantic climate systems on the Holocene paleoclimate of the Caribbean (Schmidt et al., 2004). These phenomena affected not only past societies but continue to represent a hazard for modern societies: precipitation, sea surface temperatures (SST), and hurricane development, which can impact land

surfaces and the productivity of marine resources, thus affecting food, economy, and habitat security.

El Niño Southern Oscillation (ENSO)

El Niño Southern Oscillation (ENSO) is a recurring climatic phenomenon that lasts for periods of three to seven years and triggers a change in the temperature of the waters in the Central and Eastern tropical Pacific Ocean, which warm or cool between 1°C and 3°C compared to average sea temperature (Cai et al., 2020). The oscillation between the warm and cool phases, referred to as ENSO cycles, affects the rainfall distribution and influences the weather worldwide, with marked socio-economic effects (Cai et al., 2020). The warming of sea surface temperatures (SSts) in the Pacific Ocean is known as the El Nino phase, cooler SSTs are identified as the La Niña phase, and the close-to-normal SSts are considered the Neutral phase. Each of the ENSO phases affects the word differently. In the case of the Atlantic basin, each phase affects the formation and intensity of the hurricane season due to the impacts in the Walker and Hadley circulation. The Walker circulation is a cell that is created by air rising over the ocean in the western tropical Pacific, then travels eastward high in the atmosphere before sinking back to the surface over the Eastern Pacific Ocean (

Figure 1. 1). The Hadley cell or circulation is a global-scale tropical atmospheric circulation in which warm air near the equator rises and flows poleward near the tropopause at the height of 12 to 15 kg (7.5 to 9.3 miles) above the earth's surface once the air cools down it descends into the subtropics to about 25 degrees latitudes, then returns toward the equator near the surface.

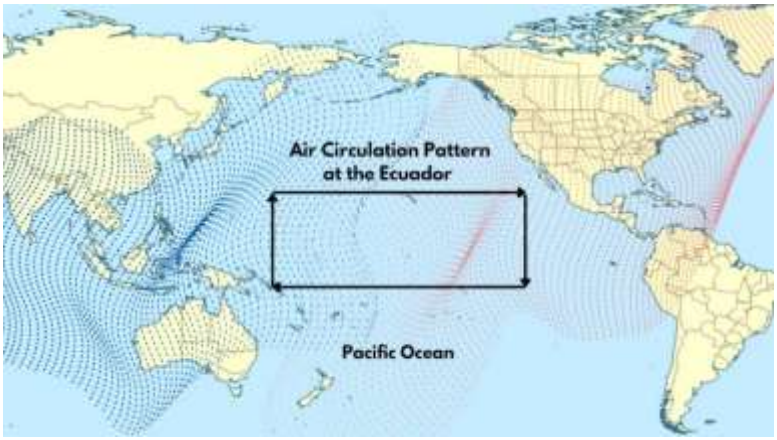

Figure 1. 1 Schematic of Walter Circulation, showing the characteristics of east-west air circulation pattern. The colored grid shows surface pressure associated with Walker Circulation, with blue showing areas of low surface pressure and red showing areas of high surface pressure. Graph prepared by M. Declet Pérez.

During El Niño, the Walker circulation is slightly weaker than average and shifts eastward; this increases the upper-level westerly winds over the Caribbean and tropical Atlantic (Klotzblach, 2011; Lin et al., 2020). The combination of the increased upper-level westerly winds with the climatological lower-level easterly winds increases the vertical wind shear; these conditions are known to be detrimental to Atlantic hurricane formation (Klotzbach, 2011; Lin et al., 2020). During La Niña and the Neutral phase, the scenario is inverse; the Walker circulation intensifies and shifts westward, thus decreasing the force of the upper- and lower-level winds; this combination reduces the vertical wind shear and increases the hurricane activity in the Atlantic basin (Klotzbach, 2011; Lin et al., 2020).

In the Caribbean, how ENSO affects the marine ecosystem and fish population is a complex question that remains open (Huang et al., 2023; Blanco et al., 2006). Some studies suggest that ENSO variability causes changes in currents and eddies in the Caribbean Sea and can potentially affect marine productivity (Haung et al., 2023; Holbrook et al., 2020). One example is the correlation between ENSO and chlorophyll in the upwelling regions, which could affect nutrient

movements from the deeper ocean (Haung et al., 2023). El Niño phase can also trigger disease outbreaks and coral bleaching in the Caribbean (Holbrook et al., 2020; Randall & Woesik, 2017). Randall & Woesik 2017, found that peaks of coral disease matched with the periodicities in ENSO conditions, while extreme coral bleaching events worldwide have occurred during strong El Niño events. In the Caribbean Colombian coast, salinity changes in estuarine areas have been linked to the effects of drought caused by ENSO events. The prolonged increase in water salinity has noticeable impacts on living communities, such as massive fish death and mangrove desiccation (Blanco et al., 2006).

Sea surface temperatures (SST)

Hurricanes start their development with the evaporation of warm seawater, which pumps vapor into the lower atmosphere. For this to occur, the water temperature needs to be over 27 ^{o}C. As higher and prolonged warm SST occurs, the cyclonic circulation will intensify depending on how long it remains over the warm waters (Esmaeili et al., 2021; Salarieh et al., 2023; Mudd et al., 2014). As the winds that move cyclonically around the storm grow and intensify, they push the ocean/sea waters toward the coast, generating intense and dangerous storm surges (Esmaeili et al., 2021; Salarieh et al., 2023; Mudd et al., 2014).

Prolonged high SST conditions can affect the coral reef ecosystem by increasing the frequency and intensity of coral bleaching. In this process, the coral loses its endosymbiotic algae, which is a primary energy source for corals. These conditions can cause coral morbidity and increase mortality, reducing coral coverage, triggering dramatic changes in coral community composition, and rapid reorganization of coral reef-fish communities (Sully et al., 2019). In the case of the estuary / riverine ecosystem, prolonged high SST or warmer conditions can increase the frequency and severity of hypersaline conditions, enhance the water column stratification and

hypoxia, and reduce flushing, leading to greater retention of nutrients (Hallett et al., 2018). These effects can shift the composition of benthic communities, decrease species richness and diversity, and reduce the number of more sensitive taxa (Hallett et al., 2018).

North Atlantic Oscillation (NAO)

The North Atlantic Oscillation is a weather phenomenon over the North Atlantic Ocean. It, consists of fluctuations in the difference of atmospheric pressure at sea level between the Iceland Low and the Azores High; it also produces changes in surface air temperatures, winds, storminess, and precipitation over the Atlantic and adjacent continents (Hurrell & Deser, 2010). Positive NAO values indicate a vast difference in the pressure between the regions. These positive values are related to warm conditions over the east side of North America and northern Europe and cold environments in southern Europe. These conditions are also associated with strong westerly winds and higher than average SST in large parts of the North Atlantic (Hurrell & Deser, 2010; Elsner et al., 2000(a); Elsenr et al., 2000 (b)). The negative NAO values indicate low-pressure differences between the regions, creating cold conditions in Eastern North America and Northern Europe and warm conditions in Southern Europe. The strength of the NAO influences the geographic variations of the sea level pressure, which is also related to the latitudinal variations in hurricane activity (Hurrell & Deser, 2010; Elsner et al., 2000(a); Elsenr et al., 2000 (b)). The presence of a high-pressure system in the Atlantic basin can influence the path of the storm in the region. For example, if the high-pressure system is located over the North Atlantic, it keeps hurricanes from recurving northward and is conducive to major Gulf hurricanes; if the high-pressure is located in an eastward position in the basin, it puts the east coast of North America in the path of recurving major hurricanes; and lastly is the system is

located farther west and south then The Caribbean is more vulnerable to hurricane path (Hurrell & Deser, 2010; Elsner et al., 2000(a); Elsenr et al., 2000 (b)).

Intertropical Convergence Zone (ITCZ) and hurricanes

The Intertropical Convergence Zone is a band of low atmospheric pressure that influences the location of precipitation bands and is driven by the moisture convergence associated with the north and south trade winds that generally collide near the equator (Byrne et al., 2018; Van Hengstum et al., 2016). The ITCZ phenomenon is highly responsive to the SST (Merlis et al., 2013; Muller et al., 2017), which changes with variation in insolation, influencing warm water distribution in the ocean and warm air inland. The ITCZ is considered to significantly influence the intensity and direction of hurricanes in the Atlantic Ocean (McCloskey & Knowles, 2009; Merlis et al., 2013). When the ITZC is positioned towards the north, the hurricane development in the eastern tropical North Atlantic is enhanced; when it is positioned towards the south, the hurricane development in the eastern tropical North Atlantic diminishes (Asmeron et al., 2020; Byrne et al., 2018; Kossin & Vimont, 2007; Martinez et al., 2019; van Hengstum et al., 2016). A southern ITCZ position indicates frequent hurricane activity over the Gulf of Mexico and the inner Caribbean. In contrast, a northern ITCZ position indicates frequent hurricane activity on the North American Atlantic coast, increasing the potential of landfalls over Puerto Rico and posing hazards for the societies and marine ecosystems (Schmitt et al., 2020; van Hengstum et al., 2016).

While mangroves and coral reefs offer protection from storms, intense events, and cumulative impacts can damage these ecosystems, often beyond recovery thresholds (Taillie et al., 2020; Rogers, 2019). Floods associated with hurricanes create high sedimentation in marine ecosystems, affecting their structure and function. Storm surge affects the water column and

benthic regions (the ecological region at the lowest water body level) and can also break and destroy coral reefs (Bruckner et al., 2005; Harmelin-Vivien, 1994; Scoffin, 1993). In mangrove ecosystems, storm surges can alter salinity (Taillie et al., 2020; Rogers, 2019), and the wind can affect mangrove structures by lowering the forest's canopy. The combination of the effect of wave action and sedimentation can shift the composition of fish and vegetation assemblage. Hurricanes can destroy habitats and cause massive mortalities, social/reproductive abnormalities, and the loss of eggs and larval stages (Mukherjee et al., 2012). The effects of hurricanes can also lead to a decrease in the abundance and richness of species of reef fish communities in the shallow reef areas because of permanent re-distribution or displacement of individuals into non-affected areas (Harmelin-Vivien, 1994; Lugo et al., 2000; Secor et al., 2019). The combination of all these hurricane disturbances can result in a significant regime shift in which the productivity of the coral reef declines and microalgae, alga turf, and cyanobacteria increase their dominance, altering the food resources available to human and non-human coastal communities.

Past Caribbean Climate Setting

Literature review

The past 2,000 years (Common Era) are a key time interval to understand climate response to natural and anthropogenic forcing mechanisms. This period is associated with several climate periods, such as the Late Antique Ice Age [LAIA536 to 660 CE], the Medieval Climate Anomaly [MCA950 to 1250 CE], and the Little Ice Age [LIA 1400 to 1850 CE] and the 20th-century warming (Figure 1. 2) (Zhuravleva et al., 2023). The LAIA and the MCA would have affected the ECA and the LCA; however, the changes in the pre-Columbian societies would have occurred more under the influence of the MCA.

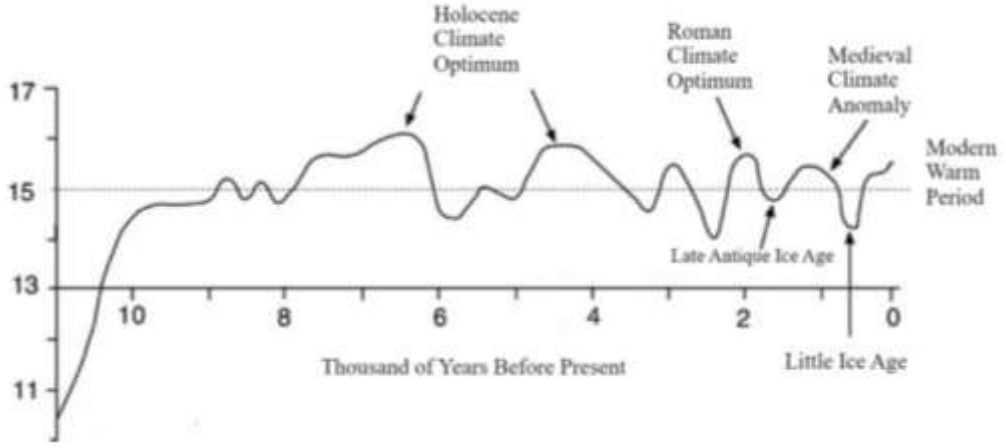

Figure 1. 2 Schematic reconstruction of average temperature variations in the Northern Hemisphere during the Holocene. Graph prepared by M. Declet Perez.

The following two graphs resume the information obtained from the literature review for the ITZC location and the Northeastern Caribbean SST (Figure 1. 3 and Figure 1. 4.)

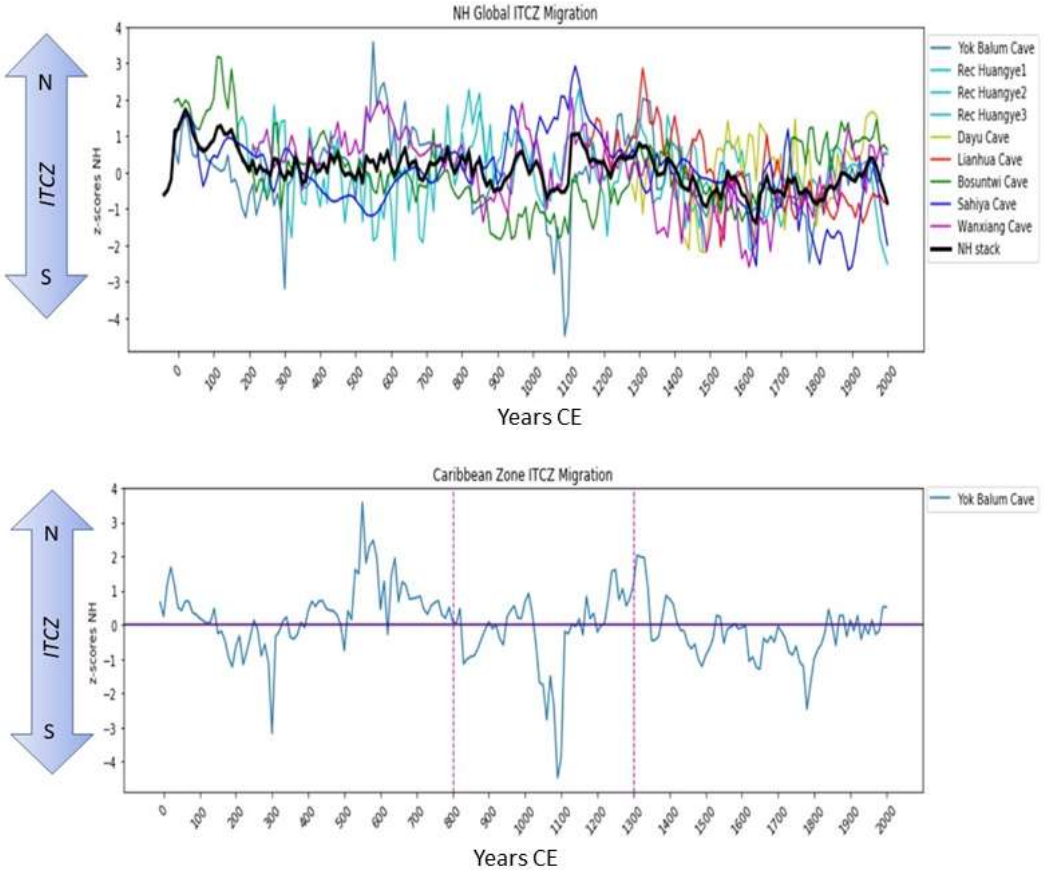

Figure 1. 3 (Top) North Hemisphere (NH) global record compilation, the black line shows the resulting stack. The stack combines 25 published high-resolution stalagmite, sediment, tree ring, and ice core records of both hemispheres; the data was processed in the modeling software COPRA using Gaussian kernel correlations. Negative values are associated with a southern position, and positive values are associated with the northern position of the ITCZ. (Data and recreation of top graph using Lechleitner et al.,2017, figure2). (Bottom) ITCZ migration on the Caribbean using the values from the York cave located in Belize; this cave is the parameter for the Caribbean region. The vertical magenta dash line delimits the transition period from the Intermediate Period to the Beginning of the Region Consolidation Period. Graphs prepared by M. Declet-Perez.

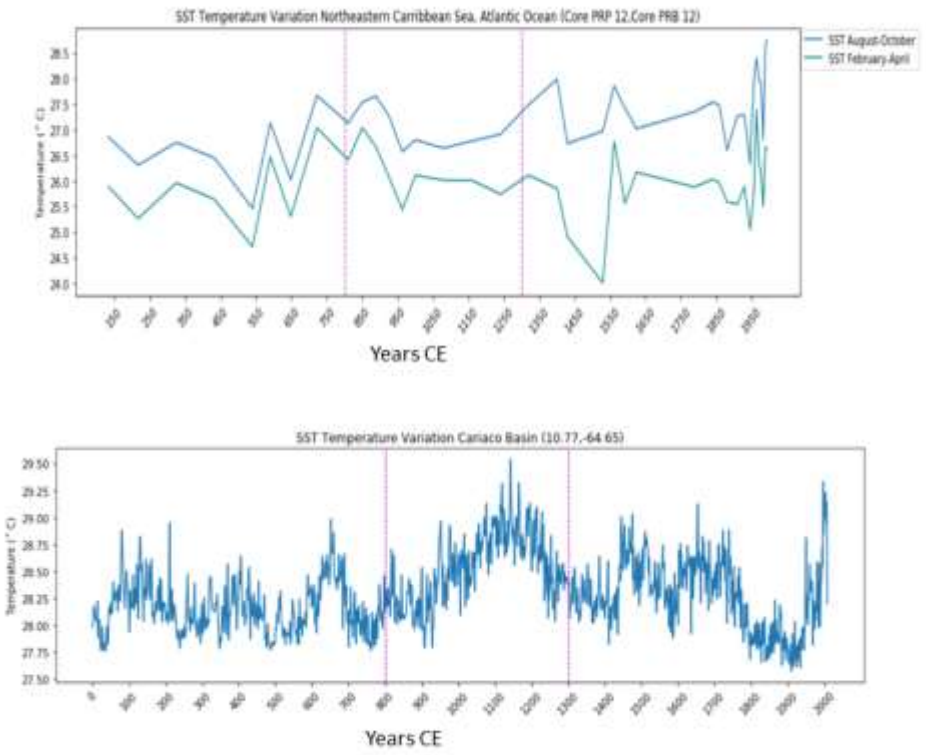

Figure 1. 4 (Top) SST measurements from two cores near Puerto Rico (Nyberg et al., 2001). (Bottom) SST measurements from the Caricao Basin (Wurtzel et al., 2013). The vertical magenta dash lines indicate the years proposed for the increment in hurricane impact in the Caribbean related to the change in the faunal components of the archaeological record seen during the transition from the Intermediate Period to the Beginning of the Regional Consolidation Period—graphs prepared by M. Declet-Perez.

Paleoclimate data from 400 to 800 CE (Lechleitner et al., 2017; Wurtzel et al., 2013) presents a predominant northern position of the ITCZ (Figure 1. 3) and SST between 25.7 and 27.5 ℃ with an anomaly of 29.0 ℃ around 600 CE (Figure 1. 4). The core sediment of Laguna Pallcacocha in Ecuador suggests few El Niño events during this time (Donnelly &Woodruff, 2007). The combination of these conditions generates ideal conditions for an interval of frequent hurricane events (Yang et al., 2024). The conditions during 800-1300 CE present a prevalent northern position of the ITZC (Brooker, 2020; Medina, 2023). The SST was consistently higher, with an average high at 29.0 ℃ and an SST anomaly of 29.5 ℃ around 1100 CE in the Cariaco

Basin core (Figure 1. 4, bottom) associated with the Medieval Climate Anomaly (Easterbrook, 2016; Keigwin, 1996; Loehle & McCulloch, 2008; Woodruff, et al., 2009; Mann et al., 2009). Interestingly, the core PRB12 from the south of Puerto Rico (17.88778, -66.60028) does not present evidence of temperatures over 28.0 ℃ during this time (Figure 1. 3, Top), suggesting that more studies or data analysis in the Caribbean are needed to understand the influence of the MCA over the northern Caribbean.

The MCA occurred around 800 CE-1400 CE, with a 200-year transition (900-1100 CE) towards higher hurricane activity (Schmitt et al., 2020). The effects of the warm temperature associated with the MCA were concentrated primarily on large parts of the North Atlantic, Southern Greenland, the Eurasian Artic, and parts of North America (Bacheler et al., 2018; Easterbrook, 2016; Keigwin, 1996; Loehle & McCulloch, 2008; Mann & Jones, 2003). During this interval, intense hurricanes and terrigenous sedimentation input increases are observed in cores from the south of Puerto Rico and throughout the Caribbean basin (Donnelly et al., 2015; Donnelly & Woodruff, 2007; Gischler et al., 2008; Holmes et al., 2023; Malaizé et al., 2011b; Nyberg et al., 2001; Wallace et al., 2021; Yang et al., 2024).

From 1330 to 1700 CE, the Northern Hemisphere recorded cooler temperatures and increased ice volume. These changes are related to the Little Ice Age (Nott & Forsyth, 2012; Wurtzel et al., 2013). The climate evidence for this interval shows ITCZ predominantly towards the south (Brooker, 2020; LeBlanc et al., 2017; Medina, 2023) (Figure 1. 3). The average SST recorded at the Cariaco Basin ranged between 26.7 ℃ and 28.0 ℃ (Figure 1. 4). The core at the Laguna Pallcacocha in Ecuador recorded frequent and strong ENSO events. These conditions favored a decrease in hurricane activity in the Caribbean, as well as a possible shift of the path of hurricanes over the Caribbean Sea and the Gulf of Mexico, affecting more directly the southern

coast of the United States (Donnelly, 2005; Donnelly et al., 2015; Keigwin, 1996; Lechleitner et al., 2017; Woodruff, et al., 2008). The period from 1700 CE to the present shows a return of a predominant northward position of the ITCZ following warmer SST and fewer El Niño events, indicating increased hurricane frequency and intensity(Brooker, 2020; Medina, 2023). Initially, higher temperatures and ITCZ migration responded to natural processes. However, since the middle of the 20th century, anthropogenic activity has contributed to the accelerated rise in atmospheric and oceanic temperature (Asmerom et al., 2020).

The data suggest that when cultural changes were seen in the Caribbean, conditions favorable for intense hurricane activity and a predominant high SST were produced under the influence of the MCA from 800-1400 CE, with the high peak of intense hurricane and high SST occurring around 900-1100 CE. These conditions could have affected the marine environment. For example, different archaeological sites on the island of Puerto Rico present evidence of flood events related to the intense storminess activity from 800 to 1300 CE (Figure 1. 5).

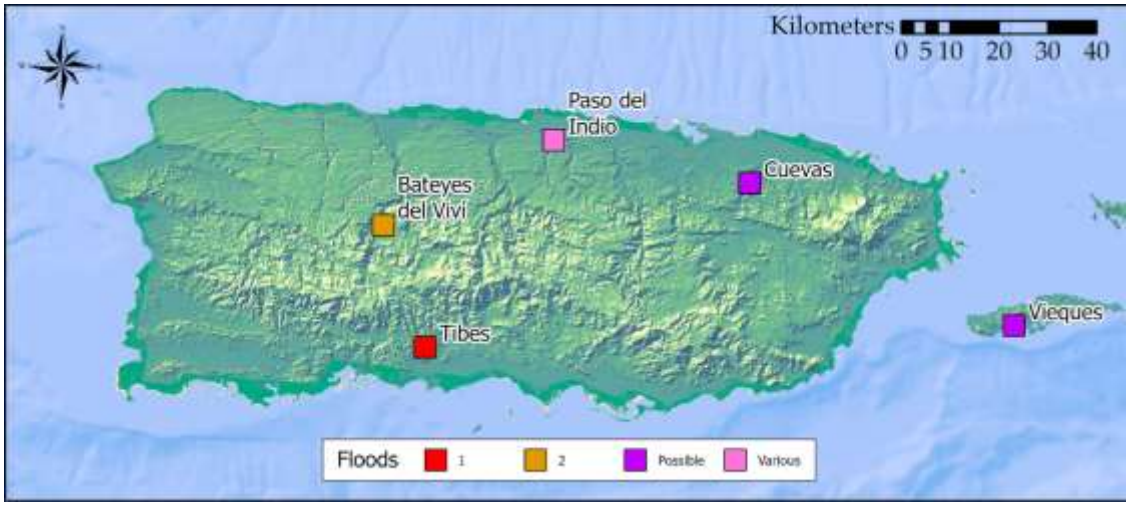

Figure 1. 5 This map of Puerto Rico illustrates the different archaeological sites with evidence of one or more flood events between 800 and 1300 CE. Graph produced by E. Rodriguez-Delgado.

Caribbean Archaeological Evidence

The Caribbean archipelago comprises over 7000 islands, islets, and cays that form an arc extending eastward to the Yucatan Peninsula and south of Florida towards the north coast of Venezuela. The arc is divided between the Greater and the Lesser Antilles that form part of the hurricane alley, a zone of warm sea temperature that extends from the Eastern Atlantic to the Gulf of Mexico and which fuels hurricane-level storm formation and intensity (Rivera-Collazo & Perdikaris, 2023). The Caribbean societies have been affected by these atmospheric events and the effects of climate change since the pre-Columbian period. In this section, we evaluate the sites of Tibes in Puerto Rico and Anse à la Gourde, Guadalupe (Figure 1. 6) to explore how changes in climate and atmospheric events during the 800-1300 CE period could have affected past societies in the Caribbean and how they responded to it.

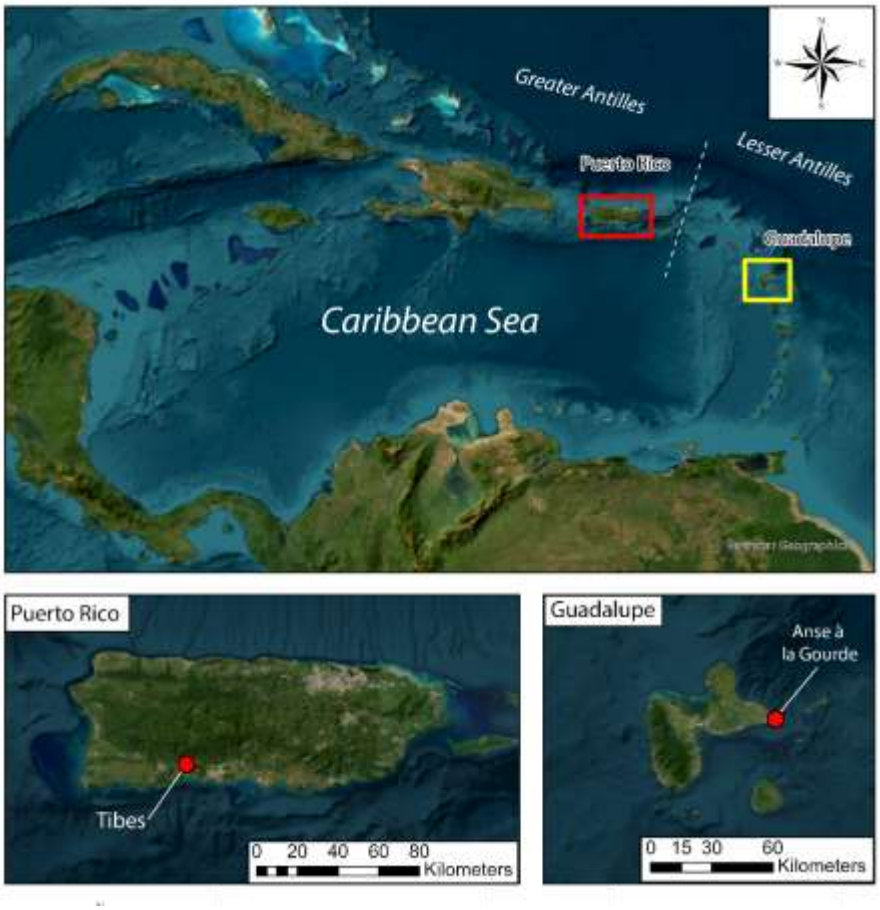

Figure 1. 6 Map of the Caribbean and the islands of Puerto Rico and Guadalupe marking the location of the archaeological sites. Graph prepared by E. Rodriguez-Delgado.

The Cultural process of the Caribbean region is divided into three major phases and is still revised due to its complexity, dynamism, and cultural scenario (Oliver, 2009; Rodriguez Ramos, 2010; Rodriguez Ramos et al., 2023). Traditionally, the naming convention for the various societies present in the region has been linked to Rouse's typological approach, even though it has been criticized for its assumption and categorization (Curet, 2004; Keegan, 2010; Rodriguez Ramos et al., 2010; Rodriguez Ramos, 2010; Fitzpatrick, 2015). His classification is based on the ceramic typology, which presents a traditional taxonomical perspective of descent based on the objects's attributes. One major problem in Caribbean archaeology is that most archaeologists tend to equal ceramic subseries to cultural units, referring to the societies as

"saladoid people" or "ostionoid people." Misusing these terms has led to confusion and misunderstanding of the social processes in the region. Therefore, to focus our attention on the social process in this article, the ceramic type is only used to refer to the pottery and not the people. Thus, the social process is divided into Initial Occupation (from the early inhabitants to ca. 400 cal B.CE), Early Ceramic Age (from ca.400 BCE to 900 CE), and Late Ceramic Age (900-1500 CE).

Puerto Rico, Greater Antilles

Tibes (300 CE to 1200 CE) is located on the east side of the Portugues River floodplain, 8km inland from the south coast of Puerto Rico, and presents evidence of the ECA and LCA (Curet,2010; Curet et al., 2006, 2016). Tibes were likely first settled permanently around 500 CE, and the ceramic found is associated with the Cedrosan Saladoid Cuevas style (400 – 600 CE). The distribution of this material in Tibes suggests that domestic structures were organized in a semi-circular arrangement, with the opening facing the river. Another ceramic style in the site associated with the ECA is the Elenan Ostionoid Monserrat style dated (600-900 CE). The inhabitants during the ECA relied on fish and shellfish as their primary animal protein source (Giovas, 2013, 2016, 2018; Grouard et al., 2019; Newsom & Wing, 2004; Wing, 2001), being the preferred ecosystem for gathering in Tibes the riverine/estuary, rocky/sand, sea grass, and coral reef (Declet-Pérez, 2018). Even though the coastal line is 8km from the site, the river provides easy access to these marine ecosystems. Another way for these resources to get to the site is by exchanging them with sites closer to the coastal area.

Around 800-900 CE, one or more flood events probably produced by one or more high-intensity hurricanes (Donnelly et al., 2015; LeBlanc et al., 2017; Lechleitner et al., 2017; Malaizé et al., 2011a; Wurtzel et al., 2013), impacted the site, triggering marked natural and cultural

changes. Using evidence from sediment cores from Laguna Playa Grande at Vieques, this flood register at Tibes has been associated with a hurricane around the same time in which an increment in hurricane activity was reported in the Caribbean (Curet et al., 2013, 2016; Woodruff et al., 2008) It is under the favorable hurricane development conditions present during the MCA that this hurricane or hurricanes are registered. The flood was a sudden event that affected the western edge of Tibes; the force with which the water came down and moved on the site is reflected in the deposition of heavy boulders lying on their side within a sterile sandy alluvium; this layer is in between cultural layers (Green, 2016). The flood layer contains cultural material and human remains, indicating that people died during the event (Curet, 2013; Green, 2016; Rivera-Collazo & Declet-Perez, 2017). After the flood, the zooarchaeological evidence indicates a change towards the riverine/estuary and rocky ecosystem as their main gathering areas of fish and shellfish return to the previous ecosystems is observed around 1050 CE as evidenced in the faunal assemblage (Declet-Pérez, 2018). The change seen in the faunal remains is also reflected in the coral assemblage. The abundance of coral decreased significantly around 850-1000 CE (Figure 1. 7). The presence of corals on the site started to increase after 1050 CE (Declet-Pérez, 2018), suggesting that the coral reef suffered from the impact of the hurricane and flood.

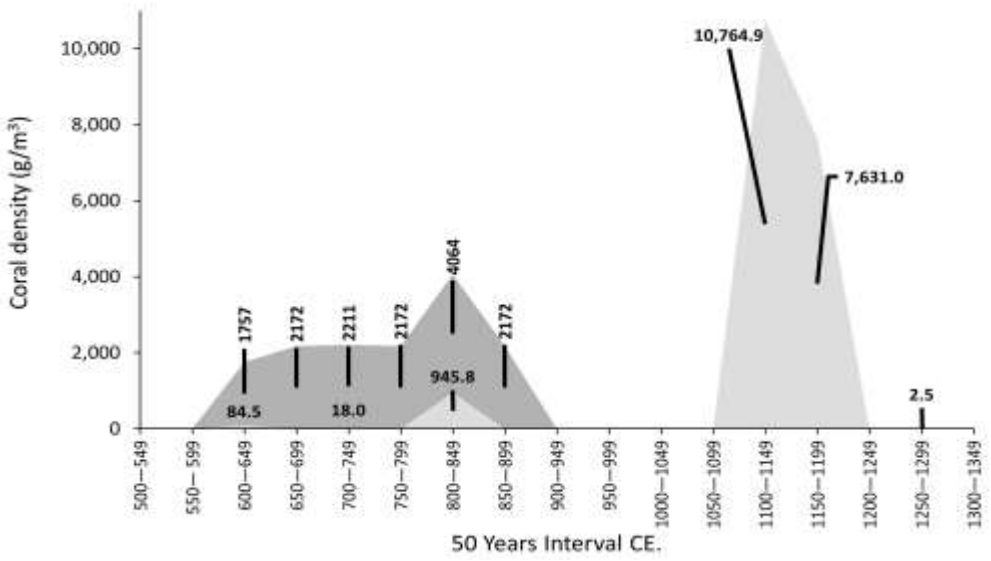

Figure 1. 7 Tibes coral chronology and density of grams per cubic per excavation level. The levels used for the chronology are only the ones classified as trash middens. The graphs show the distribution of coral throughout time with (dark-gray shading) and without (dark gray) the contribution from unit N154 E124. Graph prepared by M. Declet Perez.

After the flood event, a reorganization in the architectural structure of the site occurred with the construction of new structures, the use of garbage to level the land, and the construction of structures to divert water from the ceremonial stone structures (Curet, 2016). The structure reorganization can be seen as a response mechanism to future flood events on the site. With the construction of more ceremonial stone structures, Tibes ceased being a habitational site and became a ceremonial center. The site comprises nine ceremonial stone structures, including two plazas, one large ballcourt, and six smaller stone arrangements. These stone structures demarcate civic-ceremonial precincts and other ritual spaces (Oliver, 2022). The archaeological evidence suggests that Tibes was abandoned between 1200 and 1300 CE (Curet, 2010). No explanation has been established for Tibes's abandonment; however, the site of Jacana, ~5 km north of Tibes, presents evidence of occupation until 1500 CE. The people who were using the site of Tibes could have moved their activities towards the area of Jacana.

Anse à la Gourde, Guadalupe, Lesser Antilles

Anse à la Gourde occupies 4.5 hectares and is located on the Point des Chateaux peninsula of northeastern Grande-Terre, Guadalupe, an area vulnerable to extreme weather events (Grouard, 2001; Hofman et al., 2021). Paleoclimate data indicates that in the past, the region was exposed to climatic variations between periods of wetness and dryness; these changes are related to the different cultural phases on the island (Beets et al., 2006; Hofman & Hoogland, 2015). The three main occupational phases have been identified by the ceramic styles and radiocarbon dating as the following: 540-775 CE Late Cedrosan Saladoid, 1025 to 1270 CE Mamoran Troumassoid, and 1220 -1400 CE Sauzan Troumassoid.

During the site's early occupation, 500-700/800 CE, the village was situated on the shore of a brackish lagoon, formed by a beach barrier that allowed the formation of a mangrove forest (Hofman et al., 2021). The vertebrate faunal assemblage associated with this period indicates the exploitation of all resources available on the island (Grouard, 2003). Around 800 CE, rising sea levels caused the beach barrier to break, resulting in the lagoon's salinization (Hofman et al., 2021). The archaeological data suggest that due to this event, the village was moved to the newly formed dune; the continued retreat of the coastal line led to multiple village movements (Hofman et al., 2021) (Figure 1. 8). Beets et al., 2006;). A sterile sand layer of 20-50 cm suggests an abandonment of the site before 1000 CE; no specific date has been documented. This abandonment has been suggested to have occurred due to the climate changes registered between 800-1000CE on the island, which generated dryer and windier conditions, creating a change in the vegetation and fauna resources available (Beets et al., 2006; Grouard, 2003; Hofman et al.,

2001). More dates and resolutions on the paleoclimate reconstruction are needed to understand this process and the causes of the abandonment.

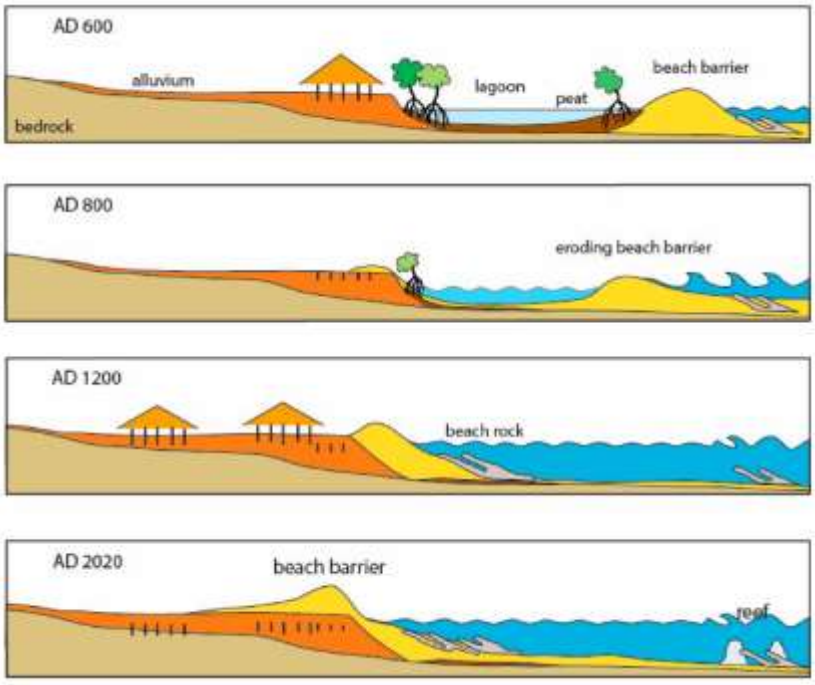

Figure 1. 8 Reconstruction of the coastal changes and gradual retreat of the indigenous settlement based on paleoclimate research from Beets et al.2006. Image from Hofman et al. 2021, created by Menno Hoogland).

Around 1000 CE, the climate changed to wetter conditions (Beets et al., 2006); this return to wetter conditions allowed the re-habitation of the site, marking the beginning of the late occupation period of the site associated with the LCA, as indicated by the presence of the Manmohan Trumassoid ceramic found in the area. These changes in the climate conditions occurred under the MCA, with increased hurricane activity. The changes in the coastal line continued, and the village was moved towards the highest elevations in the dune area (Hofman & Hoogland, 2015; Hofman et al., 2021). The food refusal in this context indicates a high dependence on marine resources, with a specialization in coral reefs (Gouard, 2003). The houses

of the village share the same characteristics observed around the Caribbean (Samson et al., 2015), described as circular or oval structures constructed with a combination of large and small pots distributed regularly throughout the building. Open walls or walls of woven vines would have allowed the breeze to circulate inside the structure, using windbreakers to mitigate strong gusts and provide sheltered areas to work in and around the houses (Samson et al., 2015). These windbreakers allow the houses to withstand the force of atmospheric events, such as those affecting the region during the MCA.

Both archaeological sites in Puerto Rico and Guadalupe present evidence of changes in their settlement configuration and structures. The analysis of these two case studies seems to support the hypothesis that at least some of the changes seen in pre-Columbian indigenous contexts could be coincident with events linked to changes in climatic variables. However, the resolution of the cultural and climatic data is not yet detailed enough, and more solid evidence is needed to articulate the chronology of events with compatible scales in both the archaeological record and the paleoclimate data.

Conclusion

Pre-Columbian societies in the Caribbean presented significant cultural changes that transformed the societies around 900-1000 CE. The diet, settlement localization, and arrangement show many of these changes. The changes in diet have been mostly attributed to the overexploitation of resources around the site. However, the potential effect of climate change and atmospheric events on ecosystems has not been extensively explored. This research focused on a literary review of paleoclimate research on the Caribbean to better understand how climate could have affected the ecosystem, in this case, the marine ecosystems and looked at two case

studies to explore if the climate conditions present during 800-1000 CE could have triggered the changes.

Climatic and environmental changes can significantly impact biodiversity and resource availability for human exploitation. These changes can create significant structural and functional changes affecting the biodiversity of coastal ecosystems. The literary review performed in this contribution allowed the identification of different climate changes that occurred in the Caribbean region and could have affected pre-Columbian societies. The main time of change seems to be around ~800-1000 CE, with evidence of changes in diet and settlement arrangement occurring in both the greater and lesser Antilles. The time in which the main cultural changes occurred has coincided with high SST and increased storm/hurricane activity resulting from the MCA. In recent years, new information and data about this warmer anomaly have helped us understand climate patterns in the Caribbean and how the changes can be related to it.

The two case studies present changes in the diet component and the reorganization location of settlements ~ in 1000 CE. However, Tibes presents more evidence of the impacts of atmospheric events in the region, providing more insight into the effects of these events on pre-Columbian societies. In the case of Anse à la Gourde, the changes seen are more related to the effects of sea level; however, during the late occupation of the site, hurricane development was favorable due to the presence of the MCA. The house structure studied by Samsom indicates that people were aware of the region's wind effects and impacts of hurricanes. However, no direct evidence of an impact by a hurricane is reported on the site or island.

The climatology in the Caribbean region is complex, and the effects depend on the island's location and how the conditions influence each region. Therefore, to better understand

how past climate change affected pre-Columbian societies, it is important to have a higher resolution on the excavation to be compared with paleoclimate records and consider other parameters or variables in the interpretation that should be considered in future regional studies.

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Chapter 2. Reconstructing Late-Holocene Climate Effects and Human Interactions on Coral Reef in Puerto Rico

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Introduction

In the Caribbean Archipelago, coral reef ecosystems have continuously been part of subsistence practices from ancient times to modern fishing communities (Kelly, 2004; Wing and Wing 2001, 1985; Wing, 1978). The sustained use of the coral reef from the initial inhabitants to the present allows us to investigate the past to identify a scenario in which we can observe the changes that have occurred in the reef due to natural and anthropogenic impacts and use it as a model to make projections of the present and future coral reef conservation projects. In Puerto Rico and other islands of the northeastern Caribbean Archipelago, the archeological record around 900 - 1000 CE presents a change in diet identified as diversification of targeted marine ecosystems and enhanced integration of inland protein sources (Carlson & Keegan, 2004; Fitzpatrick & Keegan, 2007; Newsom & Wing, 2004; Wing, 1991, 2001; Wing & Wing, 2001). Zooarchaeological analyses also identified a decline in the mean size of individual prey and a widening of the trophic level at this time (Pestle, 2013). These changes have been interpreted as resource overexploitation, which considers the impact of food procurement over ecosystems; however, the effects that climate change and atmospheric events can have on marine ecosystems and the corresponding social mitigation strategies to those changes have not been widely considered (Cooper, 2012; Cooper & Peros, 2010; Giovas, 2018, 2021; Rodriguez Ramos, 2010).

Taking into account this evidence, we focus on the island of Puerto Rico to explore the climatic conditions, paleoecology, and archaeological assemblages in tandem to determine the potential presence and areas of pre-Columbian coral reef ecosystems, whether the climatic conditions around 800 to 1000 CE would have been sufficient to create a decline or reorganization of the coral reef ecosystem that affected its productivity and impacted human interaction with the coral reef.

Coral reef Ecosystems

The coral reefs commonly associated with the modern Caribbean Archipelago formed ~130 to 200 mya after the convergence of the Caribbean and North American Tectonic Plates (Hubbard et al., 2008). The insular shelves are prime habitats for shallow and mesophotic coral ecosystems, as the wide platforms and gentle slopes allow for broader light fields that support primary productivity, growth, calcification, and nutrient transport rates for coral species. These characteristics increased the distribution and likelihood of reef formation during lower sea-level periods (Sherman et al., 2010; Kahng et al., 2019; Rouze et al., 2021). The coral reefs surrounding each of the islands in the Caribbean Archipelago are uniquely shaped by differing nutrient inputs and rates depending on their position in relation to the other islands of the Atlantic Ocean and the Caribbean Sea. In Puerto Rico, the classification of the coral reef ecosystem is based on the location and topography and is divided into regions: North, South, East, West, Mona Island, and deep reefs (Ballantine et al.,2008).

The development of reefs and the physical boundaries between systems are determined by water salinity, temperature, light penetration, sea levels, and ocean currents. Water salinity and temperature influence the coral symbiont's ability to sequester calcium and carbonate ions

from the environment to form its skeleton (Kleypas et al., 1999; Henkel, 2010). These two variables restrict the distribution of tropical coral reefs to waters with temperatures between 23-29 °C and with a salinity range of 32-40‰ (Kleypas et al., 1999; Henkel, 2010). Conditions such as turbidity, suspended sediments, and eutrophic waters (high quantities of nutrients) further affect coral species and ecosystem biodiversity due to the reduction of light penetration in the water column and increased algal growth. As water depth increases, reduced light penetration leads to a decrease in shallow-water coral taxa like *Acroporidae*, *Poritidae,* and *Pocilloporidae* (Cooper et al., 2007; Kahng et al., 2019; Kleypas et al., 1999; Henkel, 2010) which are commonly found in fore-reef areas and 15-20 m range depths in clear waters. Ocean currents associated with internal waves carry nutrients from deeper waters to shallow waters, supporting coral reef communities (Cooper et al., 2007; Kleypas et al., 1999; Henkel, 2010).

Increasing coral bleaching and tropical storms as consequences of changing climates have the capacity to change coral reef composition as they impact important variables such as water salinity, temperature, water turbidity, and nutrients. As a result of these events, coral reef ecosystems can change trajectories from phases dominated by coral reef construction towards periods of dominance from ephemeral species, octocorals or non-constructive corals (Hernandez-Delgado et al., 2024). Prolonged high sea surface temperatures (SST) can affect the reef ecosystem by increasing the frequency and intensity of coral bleaching and tropical storms impacting the region. Tropical storms, in particular, can affect coral reef ecosystem dynamics and trophic structures as the increased wave turbidity, flooding, and sedimentation from river discharge and rainfall runoff disrupt the physical and chemical properties of the water column that contribute to benthic zone ecosystems (associated or occurring on the bottom of a body water) (Wernberg et al., 2013; Bacheler et al., 2018). At the same time, coral bleaching and

storms can open the door to disease in the coral reef, adding to the reefs' decline and community reorganization. One of the most common to occur after these events and warmer sea temperatures are the outbreaks of Ciguatera - produced by the dinoflagellate of the genus Gambierdiscus found on the macroalgae and detritus of dead coral (Loeffler et al., 2021; Richlen et al., 2012). Concurrent changes to any of these variables can induce a biodiversity decline that could result in the collapse or reorganization of the ecosystem if the conditions are too prolonged or consecutive.

Although coral reefs are sensitive ecosystems, they play many important roles in our societies. They are biodiversity hotspots that provide millions of people with ecosystem services such as food provision, livelihood opportunities, carbon sequestration, and buffering against extreme climate events (Eddy et al., 2021). These services have traditionally been part of self-sufficient subsistence practice for coastal communities. Like in the past, present societies continue to use coral as tools like scrapers, files, and metates, as jewellery, and construction materials, among other uses (Lendvay et al., 2020; Tsounis et al.,2009; Li et al., 2020). Archaeobotanical evidence indicates the presence of starch in coral fragments (Pagan-Jimenez, 2011). One of the starches associated with the coral fragments is from the cojoba seed (*Anadenanthera peregrina*) (Pagan-Jimenez & Carlson, 2014). Cojoba seeds were processed with coral fragments to produce hallucinogenic powders related to the “ritual de la cojoba” used by healers for the divination of illnesses (Sued-Badillo, 2003). In Pacific cultures, the corals connect spiritually with the birth and death of the people and the islands (Gregg et al., 2015).

Case Study

As part of this study, we examine local distributions of coral species recovered from the archeological sites of Playa Muchuca (Tierras Nuevas) and Tibes Indigenous Ceremonial Center (Tibes) and their surrounding coastal areas on the North and South coasts of Puerto Rico, respectively (Figure 2. 1). The site of Tierras Nuevas is located directly on the modern north-central coast and flanked by the mouth of the Grande de Manatí River to the west of the site. Previous archaeological investigations suggest that this site was in use since ca.500 cal C.E. through Spanish Contact based on relative dating and the presence of historic materials recovered (Rivera-Collazo, in prep). Tibes, on the other hand, is an inland site located in the meander of the Portugues River at an elevation of ~68 m amsl. Radiometric approaches put the earliest occupation of the site to 300 cal. C.E. and was also in use up until 1300 cal. C.E.(Curet 2016).

Figure 2. 1 Overview of the island's study areas marking Tierras Nuevas, Manatí along the central north coast (1), and Tibes, Ponce, along the central south coast of the Island of Puerto Rico. (2). The white numbers indicate the architectural features of each site. Graph produce by E. Rodriguez-Delgado.

The selection of these archeological sites was based on their long history of utilization, availability of the material culture record, and comparable architectural features, including ballcourts (*bateyes*) and ceremonial plazas (Curet, 2010; Davila, 1979; Rivera-Collazo, in prep). Furthermore, the location of these sites on opposite sides of the island allows us to compare and contrast the conditions in the Atlantic Ocean vs. the Caribbean Sea and to see details of human dynamics on different ecosystems of the same island.

Methods

To be able to study if past climate changes could have affected the coral reef ecosystems, this research focused on three major components of analysis of archaeological composition: 1) typological analysis of coral species recovered from archaeological contexts; 2) geospatial analyses and surface modeling of modern and past coral reef distributions and availability; and 3) paleoclimate analysis through climate simulations and coral bleaching modeling. Combining these analyses, we aim to reconstruct coral reef composition and availability on the north and south coasts through time and how climate change and atmospheric events impacted them. We also analyze what effect the Medieval Climate Anomaly (MCA) had over the Caribbean Region. Under the MCA —registered around 800-1300 CE with a core period around 1000-1200 CE (Luning et al., 2017)— potentially warmer sea surface temperatures (SSTs) and enhanced tropical storm activity could have impacted the region and affected coral reef health.

Archaeological Coral Analysis

Coral fragments are an abundant and common component of pre-Columbian indigenous archaeological assemblages in Puerto Rico. This component of material culture codifies human-reef dynamics and selection of reef species and represents a human-biased sample of the coral species available at the time of occupation. Identification of coral species can shed light on the

process of patch selection and the identification of the type of reef targeted for harvest, given that coral reef assemblages in Puerto Rico vary geographically. We analyzed coral fragments recovered from previous excavations at Tibes from 1997 to 2013 and Tierras Nuevas in 2019 following the methods designed by Declet-Perez (2014 and Declet-Perez in press). This methodology consists of three main steps: (1) Taxonomic identification of fragment type, shape, and growth pattern (typology); (2) delimitation of the coral reef locations, structures, and distance around the site; (3) identification of the most abundant species by the total of the weight and measures.

The typological analysis of corals is based on Tood's (2008). All dimensional measurements were recorded with millimeter-grade resolution and recorded using plastic calipers to ensure no additional use-wear traces were created on the materials. Weight measurement and abundance were measured to a resolution of hundredths (0.01) of a gram. Use-wear analysis and species identification were conducted to identify two possible coral-gathering methods and tools in the archeological assemblage.

Geospatial Analyses and Surface Modeling of Modern and Past Coral Reef Availability

Applying geospatial analyses and surface modeling aims to understand deep-time coral reef patterns better. By focusing on the biological constraints of the species that are more abundant in the archaeological assemblages at both sites- *Acropora palmata*, *Acropora cervicornis*, and *Porites* species, it is possible to generate paleo-reef models to identify areas that could have supported ecosystems of interest to the living people on the archaeological sites at each time (see Figure 2. 2). The surface modeling was completed using the paleogeographic Python script applied by Rodríguez-Delgado et al. (2023), and geospatial analyses at 1000-yr

(highest resolution available for the area) intervals (2000-1000 CE, 1000-0 C.E.) were conducted in ArcGIS Pro.

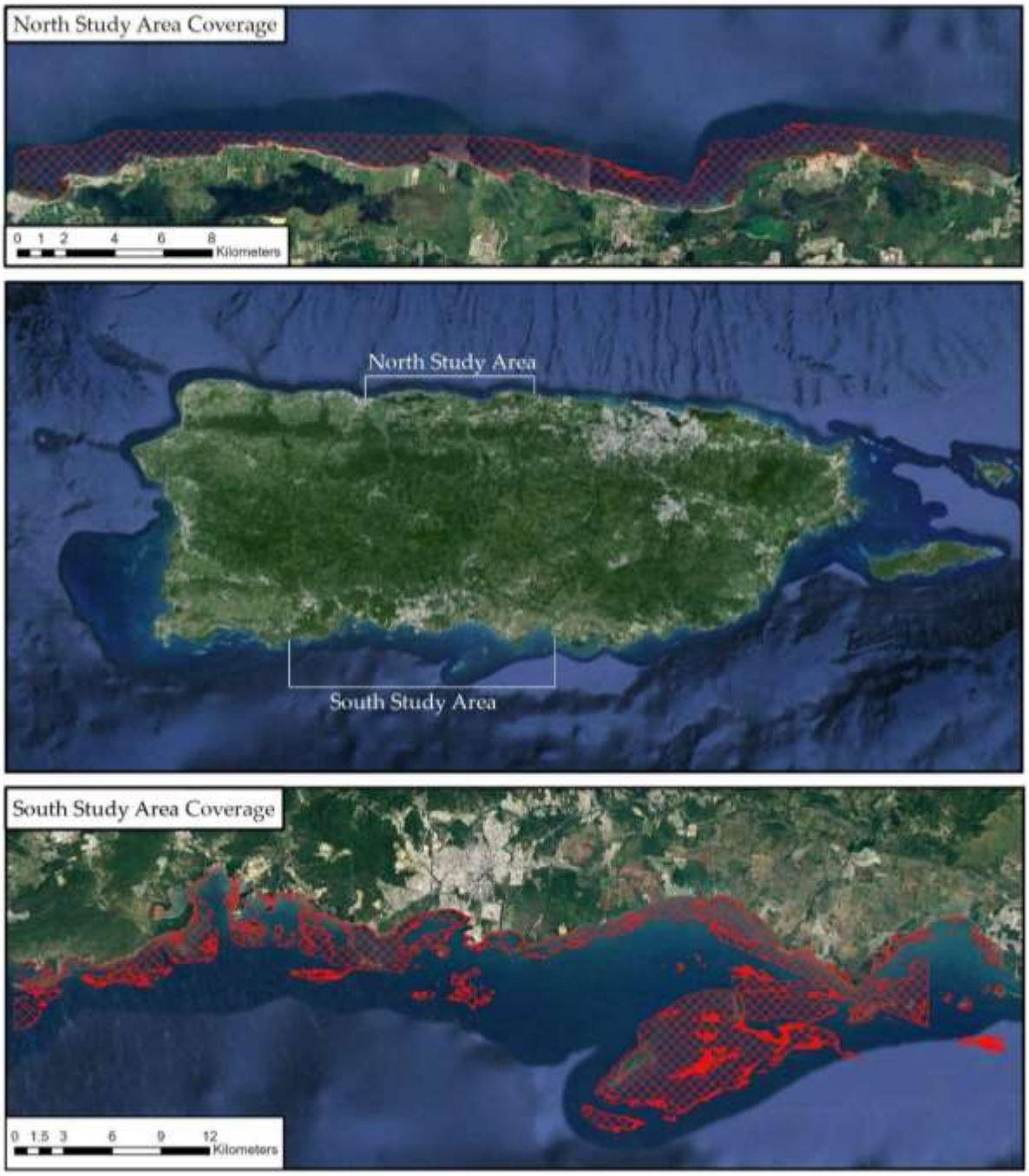

Figure 2. 2 The locations and coverage (red) of the north (top) and south (bottom) study areas extend over an area of 45.5 km2 and 156.8 km2, respectively. Graph produced by E. Rodriguez-Delgado.

The analysis incorporates modern digital elevation models (DEMs), land cover, and shallow-water benthic habitats, with modeled relative sea levels (RSLs) for the periods of interest. For our DEMs, we used a 2019 LiDAR topobathy dataset collected by Leading Edge Geomatics using a RIEGL VQ880- GII Topobathymetric lidar system (National Geodetic Survey, 2024). This dataset permits the construction of 1.0 m resolution bare-earth DEMs that extend over modern nearshore areas for the north and south study areas. To mitigate the interpretative biases stemming from modern land use and recent human activity, we filtered out areas of modern human activity identified in the latest available National Land Cover Dataset (NLCD) for Puerto Rico (Homer et al., 2004). These areas include commercial salt production, high-density urban development, low-density urban development, artificial barrens, and aquiculture. In total, these areas account for <0.03% of the total surface area and are not statistically significant. However, further details are needed to identify areas of high rural and agricultural development that may not be included in the NLCD classifications. Reconstructed sea levels are needed to model modern and past coral habitation. We used a localized RSL curve for Puerto Rico from the recent Caribbean-wide Holocene sea-level reconstruction by Khan et al. (2017). Their reconstructed heights for Puerto Rico were based on 22 index points provided by Khan and colleagues and derived from radiocarbon-dated mangrove peat samples and *Acropora palmata* corals from freshwater and saltwater contexts around the island.

Climate Model Analysis

Last Millennium Ensemble Climate Simulations

We examine the ocean and atmosphere component output of this simulation around Puerto Rico to investigate the two hypotheses regarding the climate as a factor for the diet

change during the 850 to 1000CE time period: 1) changes in storminess and 2) changes in coral bleaching. In the following, we describe two analyses we performed with CESM-LME to assess these hypotheses.

The Community Earth System Model-Last Millennium Ensemble (CESM-LME) is a set of 13 fully coupled CESM simulations covering the period 850 to 2005 CE (Otto-Bliesner et al., 2016). These simulations are forced by climate-forcing reconstructions from the Coupled Model Intercomparison Project, phase 5 (CMIP5), and effectively provide 13 plausible reconstructions of Earth's climate over this period. While the same climate forcing is applied to each ensemble member simulation, the phasing of natural (internal) climate variability is different in each simulation due to round-off level differences (10^{-14} °C) in the air temperature field at the initialization of each simulation. This allows a disentanglement of changes in the Earth system between the forced response to climate forcing (the mean of all the simulations) and natural variability in the climate system (the spread of variability in the simulations); see Deser et al. (2020) for more information on model ensembles.

Tropical cyclone genesis potential index: To assess possible changes in tropical cyclone activity during this time period, we computed a tropical cyclone genesis potential index (GPI) using the CESM-LME simulations. The model's coarse spatial resolution does not permit accurate simulation of fine-scale features of tropical cyclones. However, these simulations capture the large-scale environmental factors important to tropical cyclone genesis. The GPI is a metric of tropical cyclone activity that links large-scale environmental conditions to tropical cyclone behavior, with values of the GPI indicating that environmental conditions were more favorable for tropical cyclone formation and intensification (Emanual & Nolan, 2004; Camargo et al., 2007; Emanuel, 2010; Murakami & Wang, 2022). Although there are some limitations to

linking large-scale conditions with tropical cyclone behavior, we apply this approach here, given the absence of high-resolution storm-resolving simulations of this time period. While the GPI has been applied in many studies over the historical record and for future climate scenarios, relatively few studies have looked at tropical cyclone activity in prehistoric climates (Yan et al., 2015). Modeled storm potential can provide insight into the causes of past storm activity, complementing geologic observational records that are spatially sparse and only capture some events, e.g., above a threshold, causing overwash to appear in sedimentary records.

Of the various forms of the GPI, here we choose a simple cyclone genesis index (CGI), which is expected to be effective for Atlantic tropical cyclones during climate conditions similar to the Medieval Climate Anomaly (Bruyère et al., 2012). The CGI is computed as $CGI = \left(\frac{PI}{70}\right)^3 (1 + 0.1\, V_{shear})^{-2}$, where *PI* is the thermodynamic potential intensity calculated using monthly surface temperatures and vertical profiles of temperature and humidity (Bister & Emanuel, 2002; Gilford, 2020, 2021) and V_{shear} is the deep-layer vertical wind shear estimated as the vector difference between the upper level and lower level monthly winds. For these preliminary results, we assess one component of the *CGI*, the windshear V_{shear}. A suppression factor accounting for the suppression of tropical cyclones by the presence of wind shear (with 1 representing no suppression and 0 representing full suppression) is defined as $S = (1 + 0.1\, V_{shear})^{-2}$ (Emanual and Nolan, 2004). Future work will include the potential intensity *PI* in the analysis to compute the full *CGI*. Analysis of the results includes averaging over the main tropical cyclone development region for the North Atlantic, encompassing the western Atlantic and Gulf of Mexico: 8.758°–31.258°N, 266.258°–308.758°E (Gilford et al., 2017), and averaging in time over the peak months of the tropical cyclone season (Wing et al., 2015).

Results are not qualitatively sensitive to moderate changes to the averaging region or time period.

Coral Bleaching Modeling

To assess the possibility of coral bleaching over the 900 to 1450 CE, we extracted sea surface temperature (SST) from the CESM-LME for two regions: one covering the northern coastal region of Puerto Rico and one covering the southern coastal region of Puerto Rico, corresponding to the geographical location of the archaeological sites of interest. Corals begin to experience heat stress once temperatures exceed the normal annual maximum temperature at their location by 1-2 ° C. While most bleaching calculations use a fixed climatology of the normal maximum temperature to assess bleaching status, here we included an "adaptation metric" similar to that used by Teneva et al. (2011). This model uses a rolling climatology based on the average annual maximum temperature of the previous 50 years. As such, we used the first 50 years (850-899 CE) of the CESM-LME to compute the first segment of the 50 year rolling climatology, so we began to assess coral bleaching starting in year 900 CE. We determined Degree Heating Months (DHM) for each year of each ensemble member, computed as the sum of the excess temperature over the previous 3 months. DHM values above 1 are considered conditions that cause *moderate* coral bleaching; above 2 causes *severe* bleaching; and above 3 causes *very severe* bleaching with high mortality. Two *severe* or *very severe* bleaching events within one 10-year period is determined to be unsustainable for healthy coral reefs.

Results

The results of the modeled distribution of coral reefs provide the percentage probability of this ecosystem being present on the island's coastline (Figure 2. 3). Unfortunately, the highest resolution for paleoecological reconstruction available for the area is up to 1000 years. Between

the modern (1000-0 CE) and past (2000-1000 CE) ranges for the availability of coral reefs, rising sea levels do not significantly change the topography of study areas. Both the north and south present large areas suitable for coral reef growth. The model indicates that during the 1-2kya t, both study areas presented a 96.1% possibility of coral coverage, with a slight increment in coverage possible in the 0-1kya. In this case, the north has 97.3% and the south has 98.1%.

Figure 2. 3 Coral reef and coral favorable conditions percentage for the North and South study areas. There is no major difference in the conditions between the 1-2kya and 0-1kya.

The three main species used for the reconstruction also present high probability of coverage in the coral reef inside the study area. The *Acropora cervicornis* has major coverage on both sides of the island, with 56.7% north and 72.4% south. The modeled availability of *Porites* sp. was abundant in both north (48.4%) and south (60.1%). The modeled *Acropora palmata* was the most contrasting species in the study, with only 19.7% of the north study area providing favorable conditions for its growth vs. 45.5% of favorable conditions for the south study area.

However, when contrasting these results with what is seen in the archeological record and the current coral species distribution on the coral reef, a different scenario can indicate that additional factors, such as hyper-eutrophic conditions, may have impacted the presence of the species or human selection.

The geospatial assessment and the characteristic need for the most abundant species allow the identification of specific areas that have maintained their coral reef structures, which can be considered sentinel areas from the pre-Columbian period to the present.

Archaeological coral analysis

A total of 2,853 coral fragments (21,207.38 g) were identified and analyzed between both sites. Only 70 fragments presented evidence of intentional use-wear in archaeological contexts. A total of 1,406 fragments (3,365.93g) showed poor preservation conditions that impeded species or use-wear identification. Tibes presents higher quantities of coral overall; Tierras Nuevas has 55 of the 70 coral fragments with evidence of intentional modification and use-wear. Overall, the coral sample presents evidence of being gathered directly from the reef due to the presence of defined corallite areas and sharp edges in the borders of the fragment.

Taxonomic Identification

A total of 20 different species were identified. Not all were present on both sites (Figure 2. 4). *Acropora palmata*, *Acropora cervicornis,* and the *Porites sp.* are the most dominant species of the whole sample and were identified both in Tierras Nuevas and Tibes, although in different proportions. The species identified only in Tibes are *Cladocora arbuscula*, *Dendrogyra cylindricus*, *Diploria labyrinthiformis*, *Isophyllia sinuosa*, *Madracis auretenra*, and *Oculina diffusa*. The species identified only in Tierras Nuevas are *Agaricia tenuifolia*, *Pseudodiploria* sp., *Pseudodiploria clivosa*, and *Siderastrea* sp.

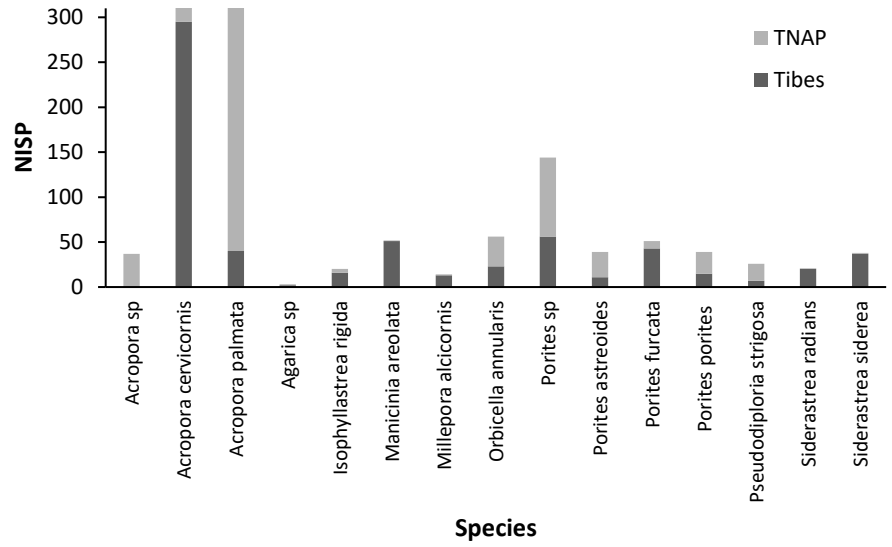

Figure 2. 4 Coral species present on both sides for Tibes (dark gray) and Tierras Nuevas (TNAP) (light gray). The Acroporidae family is the most abundant in the sample.

Each coral has a different structure, which influences the gathering difficulty for people: pillar and branch types fracture easily, and do not require tools to gather them. Meanwhile, mound and encrusting types require tools and strong techniques force to break them off the reef. The coral assemblage in both archaeological sites consists primarily of species with branch and pilar structures, followed by encrusting, mound, and boulder structures in lesser quantities. The preference towards the pillar and branch type mirrors the gathering difficulties for each type of coral.

Not all species live under the same conditions. The development and stability of the coral species depend on the environmental characteristics, and therefore, species identification of archaeological specimens can help identify ancient coral reef habitats, as shown in Figure 2. 5. Most of the coral fragments of Tibes require clear, shallow water habitats with depths around 0-20 m (habitats 1). In contrast, most of the coral fragments present in the sample of Tierras

Nuevas seem to have come from shifting, shallow water habitats with depths around 0-13m (habitats 4).

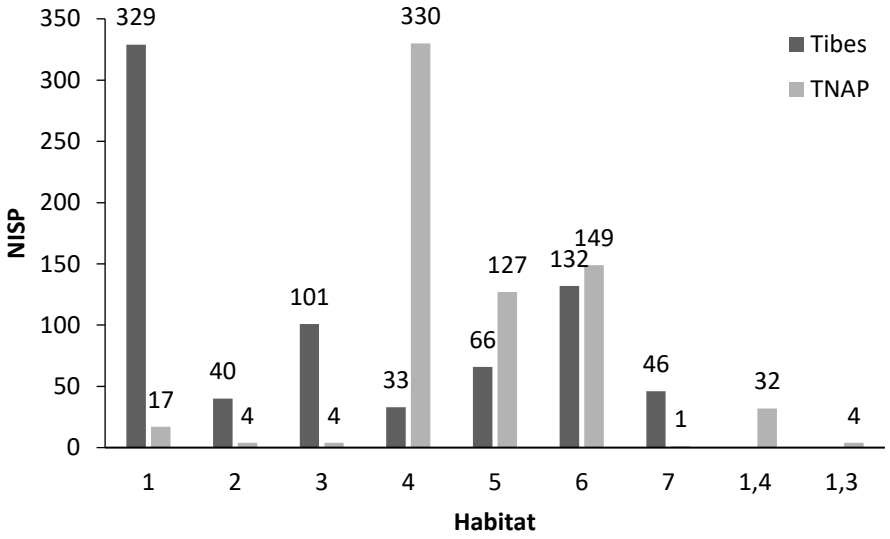

Figure 2. 5 Coral habitats derived from species in Tibes (Dark Grey) and Tierras Nuevas (TNAP) (Light Grey); 1) Shallows to moderate deeps and clear water 0-20m; 2) Shallow water with high sedimentation 1-10m; 3) Shallow water and rocky substrate 3-13mt; 4) shallows water with constant water movement 0-13m; 5) moderate deep and different environments 5-16mt; 6) moderate to deeper water 1-53m; 7) shallow water, sand, and seagrass; 1,3) Shallows to moderate deeps, clear water and rocky substrate 3-20m; 1,4) Shallows to moderate deeps, clear water with constant water movement 3-20m.

Considering the use of coral specimens through time, Tibes shows consistent numbers of corals from 600 – 950 CE, followed by a distinct peak in abundance between 1100 – 1200 CE. Tierras Nuevas, however, aside from presenting lower amounts of coral specimens overall, shows a consistent presence of corals from 800 – 950 CE, at 1100 CE, and a distinct peak with a high abundance of fragments between 1350 – 1450 CE (Figure 2. 6). Both sites show a decline or absence of corals between 900 and 1110 CE.

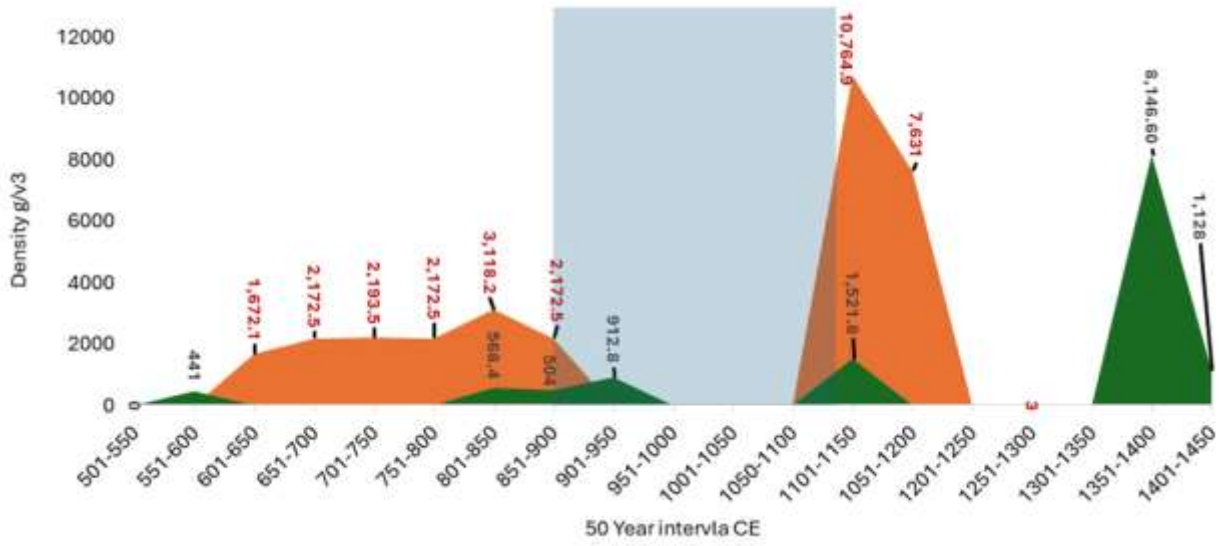

Figure 2. 6 The graph presents the change/ decline of coral presence in two archeological sites in Puerto Rico: Tibes (orange) on the South coast and Tierras Nuevas (green) on the North coast. The light blue rectangle marks when the Caribbean registered a change in the climate, and the archeological record presents changes in the cultural context. Graph prepared by M. Declet-Pérez).

Genesis Potential Index (GPI)

Time series of the wind shear (V_{shear}) and suppression parameter *S* from 850 to 1450 CE was generated for the set of CESM simulations (Figure 2. 7 and Figure 2. 8). Note that the potential intensity *PI* also influences the tropical cyclone genesis potential (*CGI*) and will be computed in future work. Increased tropical cyclone activity would be indicated for time periods with low values of wind shear (V_{shear}) or high values of the suppression parameter *S* (Figure 2. 7). Values of V_{shear} for this time period ranged from 10 to 17 m/s, with average values around 12–13 m/s. This corresponds to values of the suppression parameter *S* ranging from 0.18 to 0.30 with average values around 0.24–0.26 m/s. This indicates that the presence of wind shear suppressed the potential for tropical cyclone genesis to 25% (a 75% reduction) of the potential that would have been present without atmospheric wind shear. Near the year 1275 CE, there is a notable several year period with low V_{shear} (high *S*) in all simulations, suggesting this was caused by an

external forcing such as volcanic activity or dust (blue curves in Figure 2. 8, black curve shows the mean). Other periods with potentially enhanced tropical cyclone activity in all simulations were the several years around 1230 and 1330 CE.

Time periods with markedly high V_{shear} (low S), in which tropical cyclone activity was suppressed in all simulations, included 930, 1180, 1210, and 1260 CE (black curve in Figure 2. 8). The consistency across all simulations again suggests that an external forcing such as volcanic activity or dust is the cause. In individual simulations (Figure 2. 7 and blue curves in Figure 2. 8) representing natural variability within the climate system, there is substantial variability, suggesting that internal climate variability could have caused short time periods with significantly enhanced or suppressed tropical cyclone activity. Other than one time period with the most significant enhanced tropical cyclone activity, near 1275 CE, these results suggest that wind shear variability was relatively small over this time period, and that there is not a strong indicator that tropical cyclones were dramatically different at the time periods of interest with respect to the changes seen in the Caribbean cultures around 900-1000 CE.

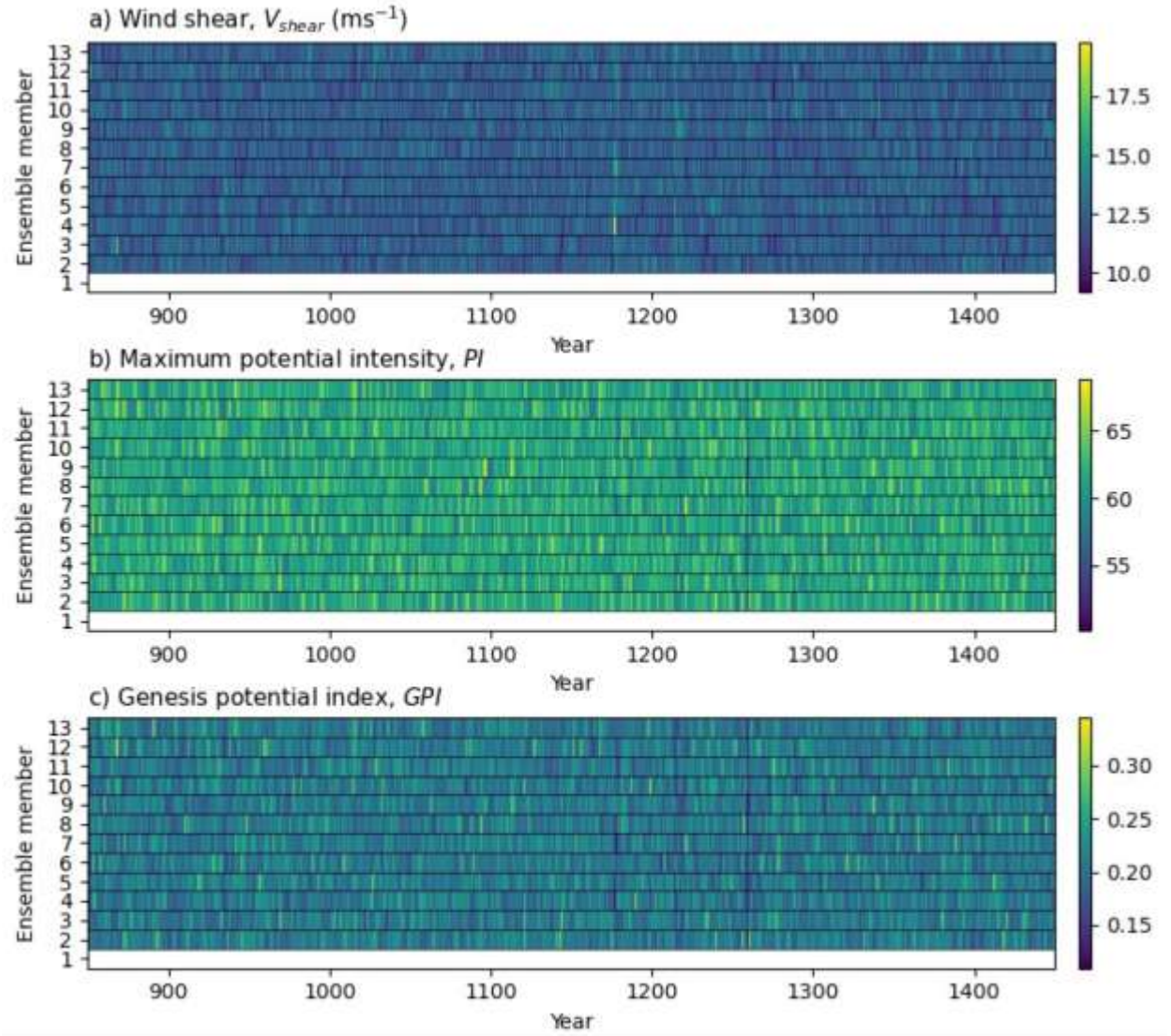

Figure 2. 7 (a) Wind shear (m/s) in the atmosphere, which affects tropical cyclone genesis, (b) thermodynamic potential intensity, and (c) genesis potential index from 850 to 1450 CE from the CESM-LME for the North Atlantic averaged over August, September, and October in each year (color scale at right of each panel). Twelve simulations ("ensemble members") of the CESM-LME are shown along the y-axis (simulation 1 is not shown due to missing data).

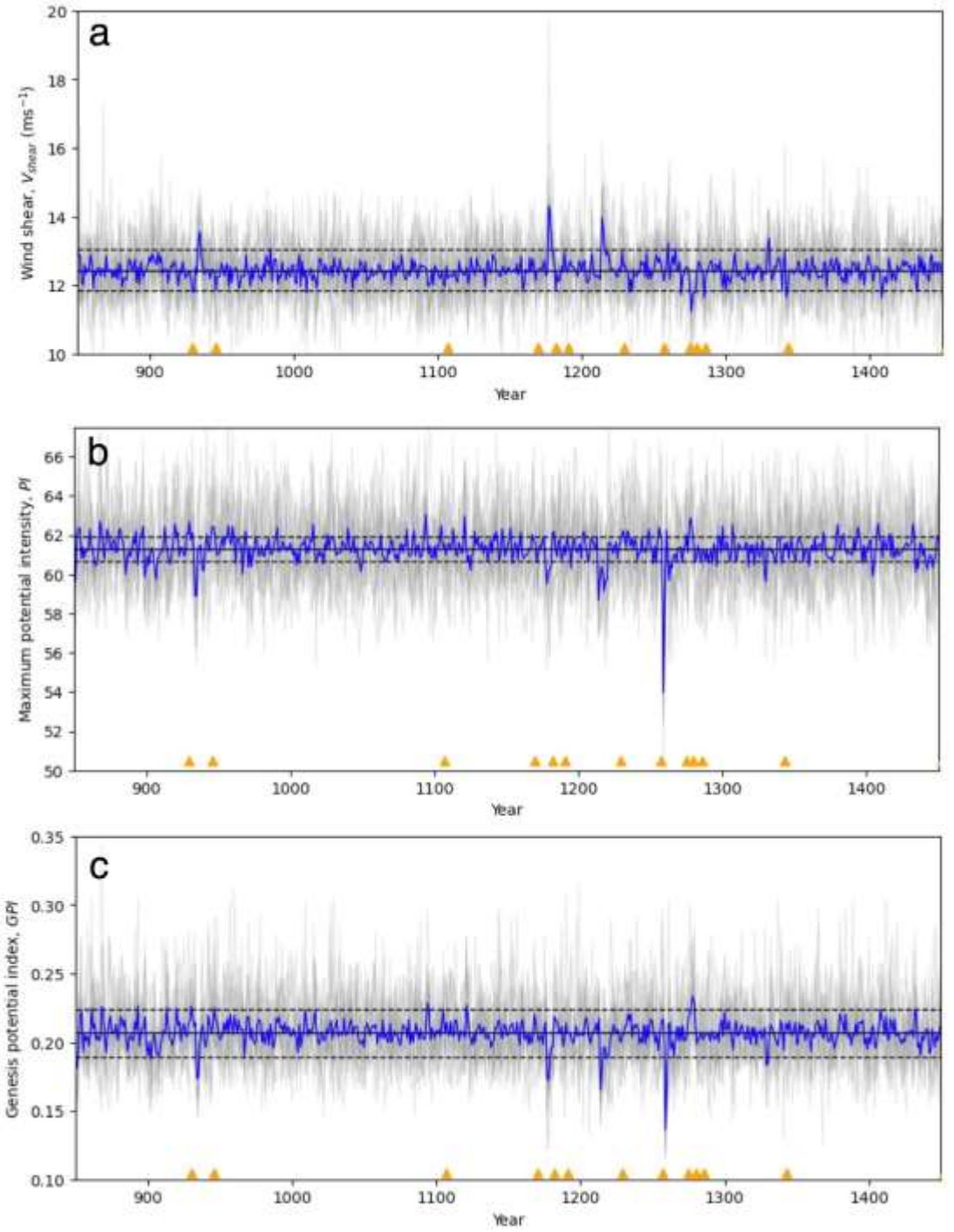

Figure 2. 8 (a) Wind shear (m/s) in the atmosphere, which affects tropical cyclone genesis, (b) thermodynamic potential intensity, and (c) genesis potential index from 850 to 1450 CE from the CESM-LME for the North Atlantic averaged over August, September, and October in each year (color scale at right of each panel). Twelve simulations ("ensemble members") from the CESM-LME are shown with gray translucent lines, and their average is shown with the thick blue line. The mean over 850 to 1450 is shown with a solid black line, and the mean plus or minus two standard deviations are shown with dashed black lines. Orange triangles indicate the timing of major volcanic eruptions.

Coral Bleaching

Coral reefs along the northern and southern coasts of Puerto Rico periodically experienced moderate heat stress, leading to some coral bleaching over the 900 to 1450 CE time period, according to the SSTs from the CESM-LME (Figure 2. 9 below). Corals frequently experienced years where DHMs exceeded 1, leading to moderate bleaching. Of the total 7150 simulated years over this time period in the CESM-LME (13 ensemble members x 550 years), coral experienced *moderate* bleaching only 7.5% of the time for the north coast of Puerto Rico and 8.1% of the time for the southern coast of Puerto Rico (see yellow bars on Figure 2. 9 below). Infrequent *Moderate* bleaching events alone would likely not cause degradation of coral reef ecosystems. Greater than two *severe* or *very severe* events repeated over a ten-year period (i.e., > 4 DHM within 10 years), however, would become detrimental and, therefore, unsustainable to the corals.

To investigate the likelihood of this happening, we calculated 10-year rolling averages of bleaching indices for each of the 13 ensemble member simulations of the CESM-LME. A 10-year mean coral bleaching index of greater than 0.4 would indicate the potential for unsustainable bleaching, marked in Figure 2. 10 by a red dashed line. The mean of the CESM-LME simulations does not exceed this threshold for North and South Puerto Rico, but the maximum coral bleaching index exceeds 0.4 during several time periods for both regions, indicating the possibility of reef degradation. For North of Puerto Rico, several peaks in maximum coral bleaching occurred during the 950 to 1100 CE time period, with additional peaks at 1200 CE, 1280-1320 CE, and 1420 CE. For the South Puerto Rico period, we observe periodic maximum bleaching indices of ≥0.5 with a more concentrated period of unsustainable bleaching during the 1080 to 1150 CE time period.

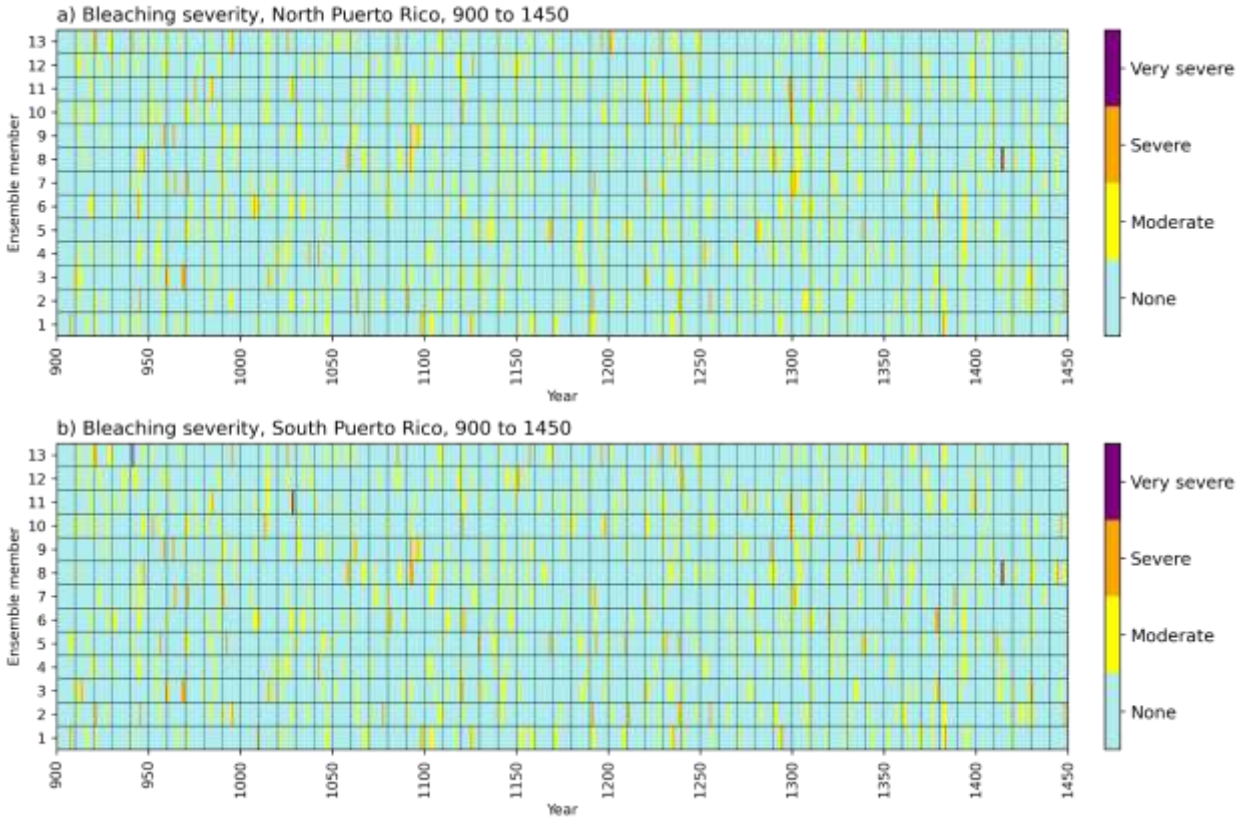

Figure 2. 9 Coral bleaching severity over the 900 to 1450 CE time period from the CESM-LME for the North Puerto Rico and South Puerto Rico coastal regions. The 13 simulations ("ensemble members") of the CESM-LME are shown along the y-axis.

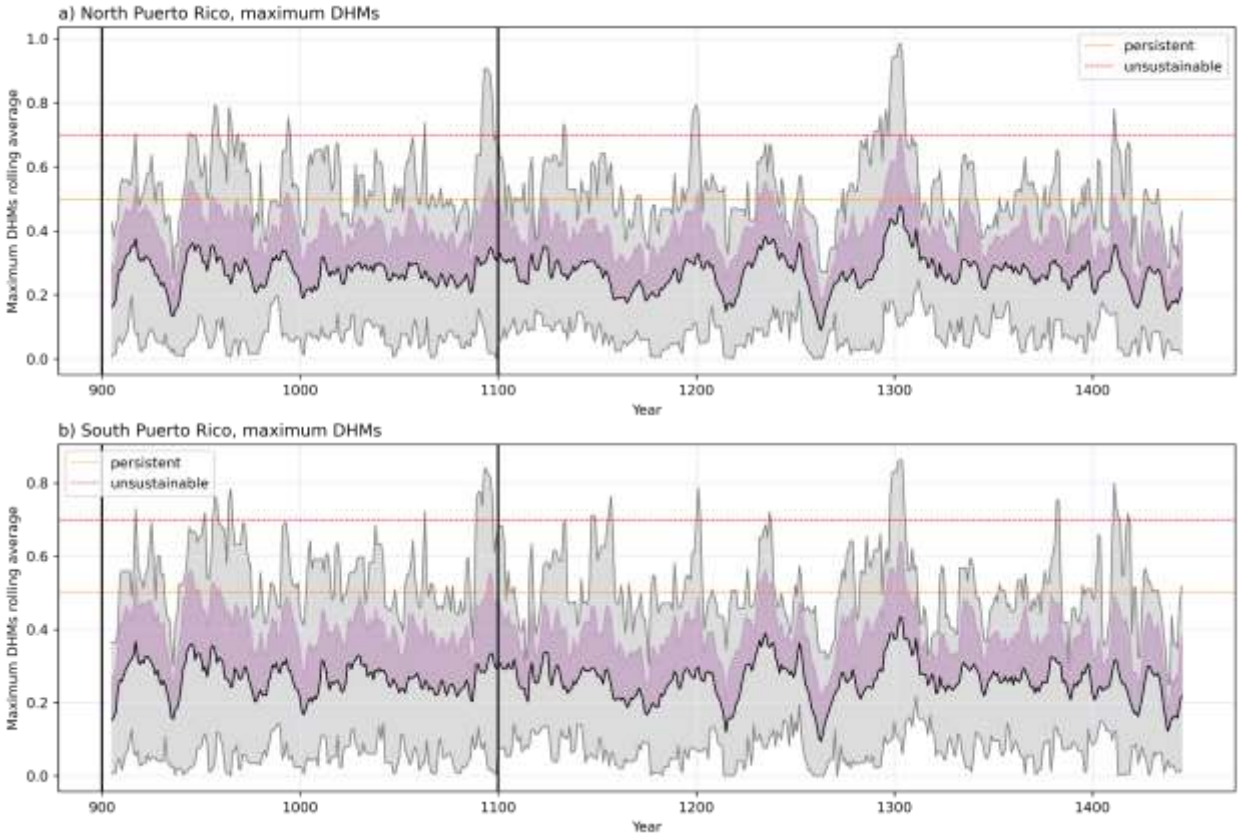

Figure 2. 10 A 10-year rolling average of maximum degree heating months (DHMs) accumulated each year from the 900 to 1450 CE period from the CESM-LME. DHMs are the sum of excess temperature over a climatological mean over three months. The black line shows the mean DHMs of the 13 ensemble members of the CESM-LME. The purple shading shows 1 standard deviation above the mean. The gray background shading shows the minimum and maximum DHMs among ensemble members of the LME simulations. The orange and red dashed lines represent the critical thresholds for bleaching; the orange line denotes when bleaching becomes "persistent," and the red line shows when coral bleaching would be unsustainable, leading to degradation of the coral reef.

Interpretation and Discussion

The geospatial analysis indicates that the coral reef ecosystem in the study areas of the north and south parts of the island has similar favorable growth conditions and locations as those seen 1000 years ago. Considering this, the coral reef in both areas of the study presents a similar distribution in the coastal area as it was 1000 years ago, indicating that the indigenous people of

Tierras Nuevas and Tibes in the past used many of the reef formations seen today. When looking at the species present in the archeological assemblage and the geospatial analysis, it was possible to delimit 6 gathering areas in the past.

The variety of species present in the assemblage suggests different coral reef structures than the one in the present; however, it is important to note that the coral present in the archaeological assemblage is more representative of the human selection process. Harvest marks and wear marks indicate that coral was collected directly from the coral reef rather than the coast and that the preferred use for the coral was as file and ground tool. In the site of Tierras Nuevas on the island's north coast, the most abundant species present in the archaeological assemblage is the *Acropora palmata*. This coral species is concentrated in high-energy shallow waters near the coastline with depths of ~0-30 m away from the high impact of sediments and nutrients from river mouths. This characteristic of the *A. palmata* allowed us to identify three areas near the archaeological site favorable for this species's growth and the other most abundant species in Tierras Nuevas, the *Porites* sp.

The first patch is the Tombolo Reef, which has an approximate area of 72,200 m^2 and a substrate dominated by a combined aeolianite and beach rock formation with depth ranges ~ 0 m to 3 m. The coral population of this reef is mainly composed of *A. palmata*, *Millepora* sp., *Palythoa caribeaorum, Pseudodiploria strigosa,* and *Pseudodiploria clivosa* (Torres-Perez et al., 2021). The second area with dense coverage of A. palmata is located towards the east between the Manati and Vega Baja municipalities (Figure 2. 11). This area has at least six big patches dominated by *A. palmata* and small sporadic colonies of *Acropora cervicornis.* The low density of *A. cervicornis* in the area is also reflected in the low density of this species in the archaeological sample. This lower density of *A. cervicornis* indicates that conditions and

characteristics of the north coast are more favorable for the growth of *A. palmata* (Hernandez-Delgado et al., 2011; Weil et al.,2003). The third area identified as a possible gathering area used by the indigenous people is the Machuca Reef, located on the front of the archaeological site of Tierras Nuevas, with an approximate area of 44,600 m^2. Unfortunately, this coral reef is considered a degraded reef and does not present the same species diversity seen in the archaeological record. However, the Machuca reef presents a high presence of the *Siderastrea siderea*, a species highly tolerant to sediment inputs. The low presence of *Siderastrea siderea* in the archaeological sample of Tierras Nuevas could indicate that in the past, the input of sediments in this region was not at the level we are recording in the present day.

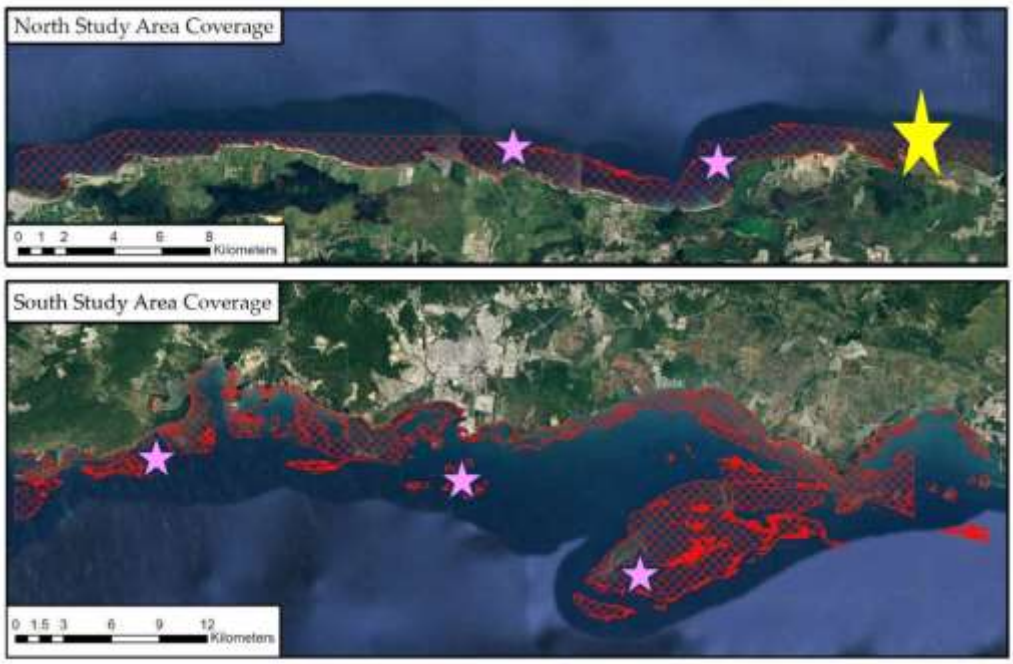

Figure 2. 11 Pre-Columbian coral reef delimitation by the use of the paleo-reconstruction (pink stars), being El Eco in the north region (yellow star) the highest concentration of *Acropora palmata* in the present. Graph produced by E. Rodriguez-Delgado and M. Declet-Pérez.

On the site of Tibes on the island's south coast, the same gathering pattern was seen as on the north coast, where the coral was gathered directly from the coral reef. In the site of Tibes, the most abundant species is the *Acropora cervicornis*. This coral species is concentrated in low-energy clear coastal waters with depths ~1-25 m but is more commonly seen at depths less than 9m away from the impact of high sediment inputs. The characteristics of *A. cervicornis* allowed us to identify three areas near the site of Tibes for this species' growth and the other species with a high presence in the archaeological assemblage. The low density of *Acropora palmata* in the present and on the archaeological assemblage of Tibes indicates that the conditions of the south coast are unfavorable for its development (Morelock et al.,1977; Weil et al., 2003). The southern insular shelf present on the south coast of the island that extends 8kn offshore provides a low-energy wave context required for the development of *A. cervicornis*. The reef associated with the island of Caja de Muertos is the first area that preset the characteristics for the growth of the species found in Tibes. The reef associated with Caja the Muerto presents an average depth of ~15m and is distant from the river mouth of Portage River in Ponce. The second area is also near the municipality of Ponce, is known as Derumbadero Reef; it is located at the fringes of the shelf-edge, 2.2 nautical miles southeast from the mouth of the Ponce Bay at a depth of 20m (Garcia- Sais et al., 2012). The third area identified is the Maria Langa Reef, located on the entrance channel of Guayanilla Bay and has a depth of ~15-16 m. Contrary to the north, the south coast benefits from lower mean annual discharge than the north, allowing the presence of clear waters.

When comparing the samples of the two archaeological sites through time, both samples present a gap or decrease in the density of coral in the sites. This gap coincided with the changes in diet reported in the Caribbean region ~800 -1000 CE; and with the evidence of flood events

registered in the stratigraphy of archaeological sites on the island (Curet, 2013; Rivera-Collazo & Declet Perez, 2017; Oliver & Rivera 2004, 2005, 2006). The paleo-climate models developed in this research allowed us to start investigating if, during this period, the climate conditions were favorable to affect the coral reef by the impact of storms and possible coral bleaching due to high SSTs needed for the development of storms.

The wind shear is an important suppression factor that affects the storm's development and strength. The CESM simulations of wind shear activity showed that the potential for tropical cyclones did not have strong trends over prolonged periods; however, some of the simulations present evidence of intense activity, indicating the probability of intense hurricanes affecting the Caribbean region in the period of ~800-1000 CE. However, there were four intervals, one of which coincided with the period under observation in which the atmospheric conditions would not allow the development of storms due to strong wind shear in the region disrupting the storm development. The strong signal of these four intervals indicates that external factors such as volcanic activity could have impacted the region, affecting the storm's development. This means that the simulations present a high variability in the potential of hurricane activity and that the possibility of having intense hurricanes during this period should not be discarded.

High SSTs are needed to develop hurricanes; their continuous presence can affect the coral reef by increasing the impact of coral bleaching. The coral bleaching models suggest that around 900-1110 CE (north) and 1080-1150 CE (south), the waters surrounding the island of Puerto Rico experienced higher than normal SSTs that could have led to coral bleaching and possible coral reef degradation. Other periods with bleaching were identified on the north part of the island, with the more severe event being a period in 1400 CE. These models suggest a possible impact of the MCA on the northern Caribbean Islands, with increased water

temperatures near the Antilles. The MCA is a climatic perturbation with a core period of 1000-1200 CE in which high temperatures are reported inland and on the ocean waters, affecting the atmospheric conditions during this period. Even though the MCA has mainly reported having its biggest effect in the northern hemisphere, high SSTs during this anomaly have been registered in the Cariaco Basin, off Venezuela, in two cores from this basin (Goni et al., 2004), and a recent study has also started to identify its effects in South America (Lüning et al., 2019). The coral bleaching models presented in this research open the door to more local investigations on how the MCA could have been registered around the Caribbean islands. Other factors that could influence water temperatures in the region, particularly on the eastern side of the Caribbean basin, is the input of continental freshwater runoff associated with the Orinoco and Amazon Rivers, which sometimes reaches the islands due to the Caribbean sea current and the occurrence of El Niño events (Gévaudan et al., 2022; Holbrook et al., 2020; Chérubin & Richardson, 2007).

Conclusion

As seen in the archaeological assemblage of Tierras Nuevas and Tibes, corals were gathered directly from the coral reef and used as part of the island's indigenous people's tool kit. The diversity of species in the assemblage and the modeled habitat availability suggest that the geomorphology of both coasts present favorable conditions for developing healthy shallow and mesophotic coral ecosystems that were more accessible and available in the past in comparison with today's coral reef systems in the island of Puerto Rico. The north coast presents a wider active water movement generated by its narrow platform, providing the conditions for a high population of *Acropara palmata,* which is reflected in the high quantities of this species in the archaeological sample of Tierras Nuevas. On the contrary, the South Coast presents a broader platform that allows calmer water conditions that favor the development of *Acropora*

cervicornis, the most representative species in the archaeological site of Tibes. The paleogeographic and archeological reconstruction results indicate that Acropora corals had a high percentage of coral cover in past ecosystems. However, the Acroporids are almost absent on both modern coasts, with some areas that- through time- have been able to resist the changes and maintain large patches of Acroporid corals, as seen on the coast of Manatí and Vega Baja.

The gap in the presence of coral in the archaeological sites, when compared against climate models, suggests a tendency more toward climate-related coral degradation than human impact on the coral reef ecosystem. The paleoclimate models suggest that the SST condition of the MCA likely triggered coral bleaching between 900-1110 CE (north) and 1080-1150 CE (south), destabilizing the coral reef ecosystem. It is possible that these unstable conditions affected the availability of resources of traditional economic importance for the pre-Columbian Indigenous societies living in Tibes and Tierras Nuevas. More robust datasets in storm genesis modeling are underway to increase the resolution of tropical hurricane events and examine their impacts. However, sedimentation records on the island suggest several high-magnitude flood events occurred during the MCA years. The models presented here are a step forward in bringing more tools to answer the question: What role could climate have played in the changes seen in the Caribbean societies around 800-1000CE?

The combination of the paleo reconstruction results and the paleoclimate presents data that is relevant for understanding how past climate changes affected the marine ecosystem and how the pre-Columbian societies were affected, but it also presents information that can serve current coral reef restoration projects in the island of Puerto Rico. By locating coral reefs used by past societies and that have encountered climate conditions similar to the current warm anomaly,

it is possible to locate resilient Acropora populations that can serve as biomarkers for restoring coral reefs on the coast of Puerto Rico.

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Chapter 3. Sustainable and Local Traditional Fishing knowledge: a New Case from Manatuabón Valley, Puerto Rico

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Abstract

In the Caribbean, pre-Columbian societies' dietary component changes have traditionally been interpreted as an overexploitation of resources. However, new research, especially in the Lesser Antilles, has identified a sustainable practice by indigenous peoples that allowed a stable and continuous species presence over time. This paper investigates the long-term use of marine ecosystems on the north coast of Borinkén, Puerto Rico, specifically in Angosturas and Tierras Nuevas sites in the Manatuabón Valley. The selection of these sites allows for studying the deep and long-lasting human and environmental interactions in the same geographic locality from 4000 BCE until the contact period. While landscape and climate changes through time modified the availability of marine ecosystems in the region, human societies consistently sought key fish species and maintained their presence over time. We propose that this observation indicates sustainable fishing practices, mediated by the use of similar fishing equipment over time, indicating the transference of traditional ecological knowledge in the form of ecosystem information and fishing traditions through generations.

Keywords: Size Estimation, Fishing traditions, Sustainability,

Introduction

Archaeological faunal remains in the Greater and Lesser Antilles not only underscore the importance of marine ecosystems for past coastal sites (Shev et al., 2023; Giovas,2021; Lefebvre, 2007) but also provide crucial insights into past human societies and the utilization, exploitation, and health of ancient ecosystems (Giovas, 2021; Buss et al., 2023). The analysis of the faunal remains in the Caribbean region presents a variation and changes marked around 900-1000 CE in which a diversification of targeted marine ecosystems and enhanced integration of inland protein sources occurred (Carlson & Keegan, 2004; Fitzpatrick & Keegan, 2007; Newsom & Wing, 2004; Wing, 1991, 2001; Wing & Wing, 2001). These changes have been associated with pre-modern anthropogenic impacts in marine ecosystems that result in the reduction in the size of fish and mollusks and local prey depletion indicated by declining abundances and shifts in species exploited (Giovas, 2021; Lefebvre, 2007). Isotopic analysis of human remains indicates a decline in the trophic levels of fish consumed by pre-Columbian societies (Pestle, 2013). The changes seen in the faunal remains and their isotopic traces have often been attributed to resource overexploitation (Wing, 2001; Wing & Wing, 2001; Quitmyer, 2003; Carlson & Keegan, 2004; Steadman & Jones, 2006; Lefebvre, 2007). Recent studies indicate sustainable fishing and mollusk, especially in some of the smaller islands of the Caribbean, indicating a more sustainable relationship with the marine ecosystem (Giovas, 2021; Bochaton et al., 2021; Carder & Crook, 2012; Carder et al.,2007; Giovas, 2016; Giovas et al., 2013; Grouard, 2001).

Current studies, led by Declet Perez 2018 and Declet et al., have identified a decline in coral reef fragments in at least two sites on the island of Puerto Rico around the same time the faunal remains and diet changes are registered in the Caribbean. This observation correlates with the impact of the increase of hurricanes and several coral bleaching events that affected the

island during this period, influenced by the Medieval Climate Anomaly and other natural factors (Schmitt, 2020; Declet Perez et al., in preparation; Yang et al., 2024). This change in climate conditions might have negatively affected coral reefs and other marine ecosystems in Puerto Rico and around the Caribbean, as seen in the work of Rivera-Collazo and Perdikaris 2023.

Climate change is not the only aspect to consider when evaluating the availability of resources; landscape change can also contribute to changes in the faunal composition (Klimaszewski-Patterson & Mensing, 2020; Rivera-Collazo 2011, 2015). Paleolandscape reconstruction models help understand past human behavior by assessing resource distribution in the landscape (Rivera-Collazo et al., 2021). This is an important note since significant landscape changes can affect the interpretation of ancient societies (Rivera-Collazo et al., 2021).

Considering this, we focused on the island of Puerto Rico to investigate whether the landscape and climate changes occurring during the early Holocene affected the availability of marine resources for past pre-Columbian societies. We would look at the ichthyofauna assemblage to see changes in its composition, diversity, and size throughout time, and this will allow looking more in-depth if: 1) the ichthyofauna assemblage presents evidence of resource overexploitation or sustainability throughout time; 2)whether or not the changing landscape and climate, affected the availability of marine resources (a.e. coral reef); 3) and how people interacted with the changes in marine resource availability.

Background

Location and Cultural setting of Angostura and Tierras Nueva's

Angostura and Tierras Nuevas archaeological sites are located on the alluvial coastal plain in the Valley of Manatuabón, in the municipalities of Barceloneta and Manati (Figure 3. 1). Angostura consists of four large mounds located over natural limestone promontories, grouped in

an area of 6.2 hectares about 3.6 Km from the coast of the Atlantic Ocean. At present, Angostura is ~600 m from the main meander of the Grande de Manatí River and has a seasonally flooded wetland within the sire, just south of the mounds (Rivera-Collazo, 2011). Eleven radio-carbon dates were obtained from the site, the oldest dating back to 4010 cal BCE (5960 +/- 250 uncalibrated)(Rivera-Collazo, 2011). The archaeological assemblage recuperated from the site includes lithic materials, ceramics, shells, and faunal remains. The dating and the material indicate that the site forms part of the early indigenous populations of the Antilles with varied subsistence and settlement strategies (Narganes Strode, 2011; Rodirguez Ramos, 2010; Rivera-Collazo 2011, 2015).

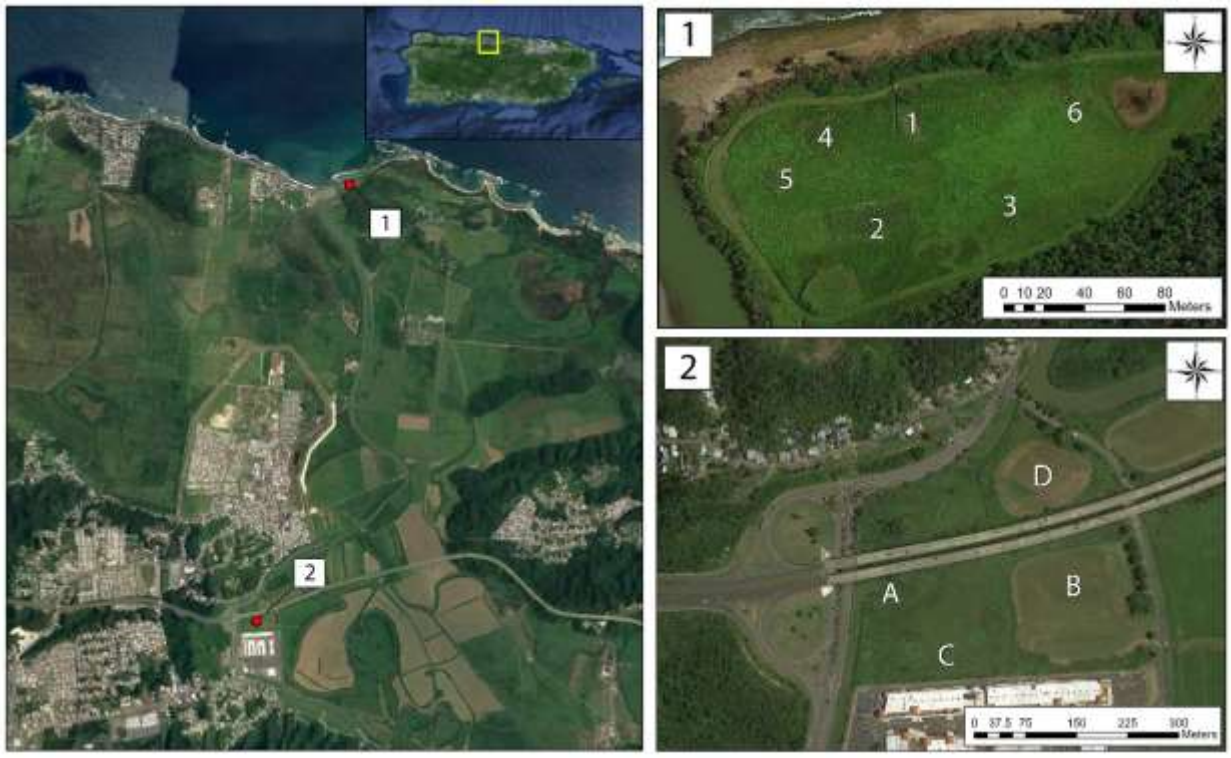

Figure 3. 1 Overview of Tierras Nuevas and Angostura archaeological sites in Puerto Rico. Figure prepared by E. Rodriguez-Delgado.

Tierras Nueva's is located directly on the modern north-central coast and flanked by the Grande de Manati River to the West, an aeolianite hill possibly formed during a time of high sea level (possibly pre-Holocene) to the south and east, and the Atlantic Ocean to the North (Figure 3. 1). The site consists of a triangle-shaped terrace measuring 280m, east-west and 130m north-south. It also comprises of six possible plazas, at least six mounds, and one clay pit. The site is considered the only surviving coastal archaeological site with plazas and mound architecture in Puerto Rico.

Research so far reveals the site to have been an administrative/ ceremonial location from its inception, meaning that no clear evidence of domestic habitation has been identified yet. The earliest radiocarbon data recovered from the site was obtained at the base of Plaza 1, the central architectural feature on the site corresponding to 430 calCE (1570±20 ^{14}C years). While excavations in the 1970s reveal the presence of the Hacienda Grande style of Saladoid pottery in one of the test units, more recent research has mostly identified later styles of Saladoid ceramics combined with multiple styles of Ostionoid pottery. The site has revealed a complex material culture assemblage, including lithics, pottery, food refuse, and tools made with different raw materials. The distribution of the artifacts reflects ritual / ceremonial rather than domestic activities. The chronological analysis suggests habitation from 430cal CE to after 1600 calCE with a possible temporal gap between 950 – 1250 calCE. The stratigraphy, however, does not show a clear abandonment, and the absence of dates may be related to a sampling gap and not site abandonment. The site was also the stage for the first attempt of Spanish settlement by Juan Ponce de Leon (Davila,1979). Research in the 1970s recovered two 16th-century coins (1505, minted in Santo Domingo) (Davila, 1979). Radiocarbon dates support Indigenous presence after the 15th Century event.

The cultural chronology of the Caribbean, especially on the island of Borikén, the largest of the Archipelago of Puerto Rico, has been and still is revised due to its complexity, dynamism, and plural cultural scenario(Oliver, 2009 ; Rodriguez Ramos, 2010; Rodriguez Ramos et al., 2023). The naming convention for the various societies has been traditionally linked to Rouse's typological approach, even though it has been criticized for its underlying assumptions and categorization (Curet, 2004; Keegan, 2010; Rodriguez Ramos et al., 2010; Rodriguez Ramos, 2010; Fitzpatrick, 2015). Rouse's classification is based on ceramic typologies, which stem from a traditional taxonomical perspective of descent based on the object's attributes. In this case, the largest category is the series, which is identified by the ending – an -; followed by the subseries, identified by the ending – oid; and then the style, identified by the name of the type site. When applying this system, the correct way of identifying a fragment of Cuevas pottery, for example, would be Cedrosan Saladoid, Cuevas style. This typological system was initially developed to support the identification of cultural units by establishing the relationship between the identified ceramic traditions with other components of the material culture – or what Cruxent and Rouse identify as associated artifacts (Cruxent and Rouse 1961). In practice, however, most archaeologists focus almost exclusively on pottery, equating ceramic subseries to cultural units. Therefore, it is common to find references to the "Saladoid people" or the "Ostionoid people" in the archaeological literature, even though these terms should only be used to classify ceramic subseries. This has led to confusion and misunderstandings with a hyperfocus on pottery and simplifying or distorting other social processes.

In this article, we will use ceramic types only to refer to pottery and not to people and will focus our attention on social processes through time. In this sense, we subdivide time as Initial Occupations (from the earliest inhabitants to ca. 400calBCE) to refer to the social

processes before the arrival of the people who used the Saladoid series pottery (Rodirguez-Ramos 2010) . The Early Ceramic Age (from ca. 400cal BCE to 900CE) refers to the initial interaction processes between the original occupants and the new migrants (Heckenberger, 2013). It is characterized by the presence of people using Cedrosan Saladoid and Huecan (Huecoid) series pottery and the beginning the Ostionan Ostionoid as a different series of pottery of local origin, probably with influence of traditions with roots in the Initial Occupations period (Rodriguez-Ramos, 2010; Oliver, 1999). The Late Ceramic Age (900 – 1500) is characterized by increasing social complexity and systematization of ritual (Oliver, 2009, Curet, 2005). In the archaeological record, there is a general decrease in the use of ceramics of late Cedrosan Saladoid styles and the development and increase of styles of the Ostionan series (Ostionoid and Chicoid), although this process is not even equal or contemporaneous throughout the island (Curet, 2005; Rodriguez-Ramos, 2010; Oliver, 2009).

Based on the dates and ceramics obtained for the site, Tierras Nueva was initially occupied during the second half of the Early Ceramic Age. This means that Tierras Nuevas development occurs when other complex sites around the island, such as Tibes, Villon/Cuyón, and Jacana, start to emerge (Torres et al., 2014). The ceramic assemblage from Tierras Nuevas includes wares with attributes consistent with styles of the Cedrosan Saladoid and Ostionan Ostionoid series. There is an overlap among and between the different stylistic manifestations, suggesting possible cultural plurality on the site (Rodriguez-Ramos, 2010; Rodriguez-Ramos et al., 2023). An early radiocarbon date (2.8k cal BCE) at the base of Tierras Nuevas coincides with the dates from Angostura, just 3.5 km upriver, and suggests the possible use of this coastal setting during the Initial Occupations Period. By looking at Angostura and Tierras Nuevas, this research will cover the early settlers of Puerto Rico up to the Spanish invasion and will examine

the ichthyofauna remains across both archaeological contexts to understand how the people interacted with the marine ecosystems and the landscape and climate changes throughout time.

Paleo landscape and climate setting

The island's coastal landscape has changed dramatically since the late Pleistocene due to changes in sedimentation accumulation along the coastal line and sea level rise. Depending on the period of habitation, the population could have confronted different coastlines and the availability of marine resources. Rivera-Collazo (2011) recreated the paleo landscape for the Manatuabón Valley using sediment cores. Figure 3. 2 shows the landscape changes in the study sites from the late Pleistocene to the present. The site of Angostura was established during the condition presented around 4.1 kya, as seen in Figure 3. 2(b). The sea level rose during the end of the Pleistocene and the Early Holocene, and the eroded landscape was submerged, creating a deep-water marine basin and estuary for the Grande de Manatí River. The site of Tierras Nuevas was established around the conditions of 1.3 Kya (Figure 3. 2 (c)), during which the sedimentation into the closed basin began silting up the coastal plain and changing the river flow (delta marked on grey)(Rivera-Collazo, 2011). Possible sand accumulation at the ancient river mouths detached the basin from an exchange with the sea, creating a shallow, probably brackish or freshwater, evaporitic lagoon known today as Tiburones Marsh (Rivera-Collazo, 2011). Human activity in the region could have been a factor in the intensification and continuation of siltation, leading to the extension of the coastal plain, leaving a small estuary at the river mouth, and shifting the boundaries of the Tiburones Marsh (Figure 3.2 (d)). Currently, the area presents extensive sand dunes accumulation on the coast and a wide alluvial plain. The Tiburones marsh is smaller due to

continued human impact, in this case by the building of a canal to drain the coastal plain for sugar-cane cultivation (Figure 3.2 (e)) (Rivera-Collazo, 2011).

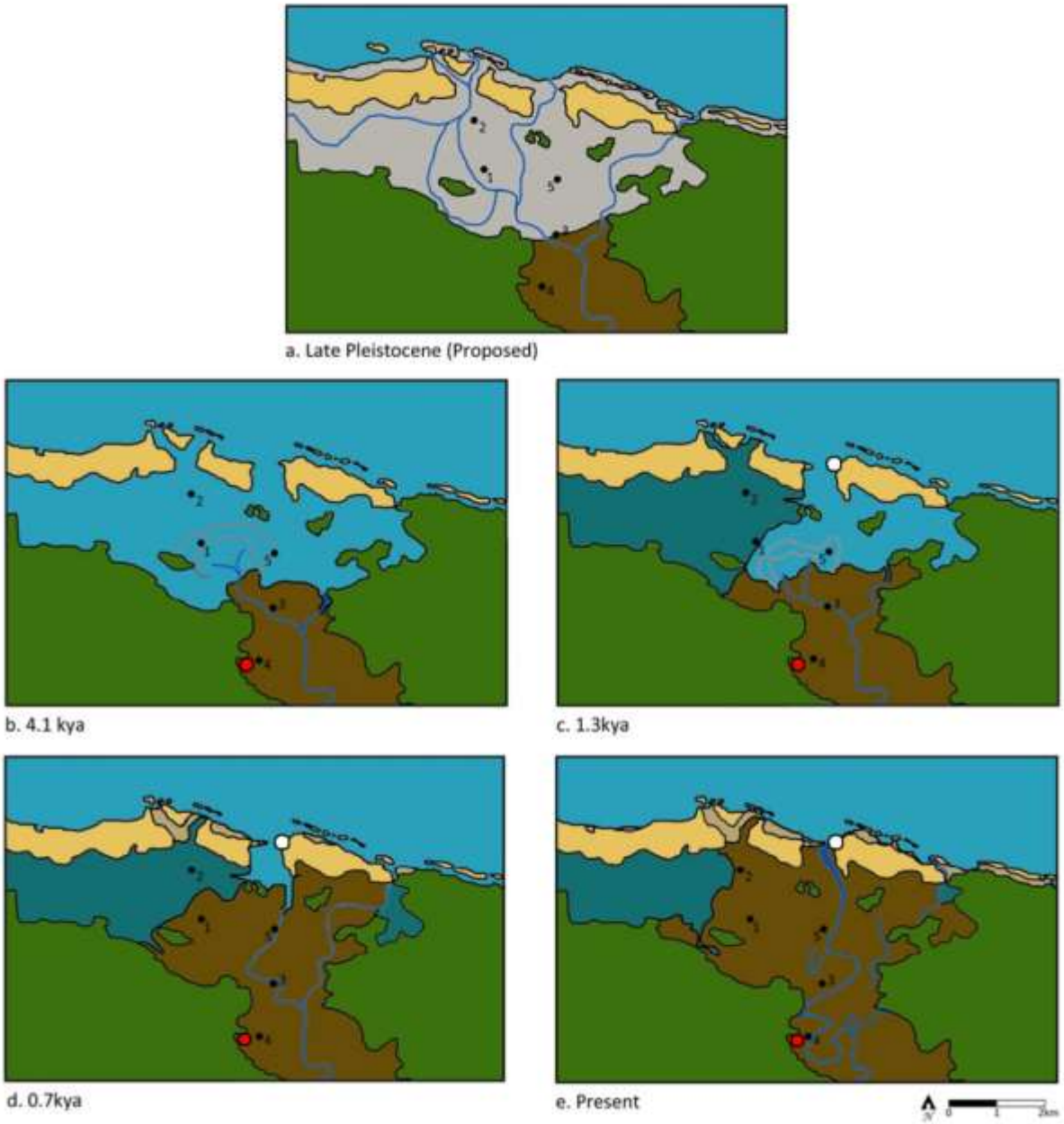

Figure 3. 2 . Modified from Rivera-Collazo (2011) proposed a landscape change process for changes in sea level and coastal plain alleviation based on the interpretation of the cores' topography, bathymetry, and sedimentology of the cores.The red dots marks Angostura, white dots mark Tierras Nuevas, and the black dots indicate the location of the sediment cores. [Color codes: unknown characteristics; aeolianite; sand; alluvial sediment; karst/limestone; river; marine water/sea; brackish water/marsh].

Landscape and climate changes can affect marine resources and impact the human communities that use them. Paleoclimate reconstruction and models indicate the presence of at least four climatic phases that could have affected Caribbean social processes Table 3. 1 (Declet-Perez et al., in prep.; Zhuravleva et al., 2023; Malaizé et al., 2011; Serrand, 2021).

Table 3. 1 Four Climatic phases that could have affected Caribbean Social processes (Declet-Perez et al., in prep; Zhuravleva et al., 2023; Malaize et al., 2011; Serrand 2021).

Date	Climate	Description	Reference
250 BCE to 400 CE	Roman Climate Optimun	Unusually warm weather in the Northern Hemisphere	Livse et al., 2016; Zhuravleva et al, 2023
536 to 600 CE	Late Antique Ice Age	Rapid cooling of the Northern Hemisphere	Zhuravleva et al, 2023;Malaizé et al., 2011; Serrand, 2021
950 to 1250 CE	Medieval Climate Anomaly	Warm climate in the North Atlantic Region, elevated sea surface temperatures	Zhuravleva et al, 2023 ;Malaizé et al., 2011; Serrand, 2021
1400 to 1850 CE	Little Ice Age	Pronounced regional cooling in the North Atlantic region.	Zhuravleva et al, 2023 ;Malaizé et al., 2011; Serrand, 2021

The climate changes and conditions present during the Medieval Climate Anomaly (MCA) were the predominant during the changes seen in the Caribbean around 900-1000 CE. During this period, several archaeological sites in Puerto Rico present evidence of flood events associated with hurricane activity (Curet et al., 2013; Curet & Pestel, 2016; Oliver & Rivera Fontan 2004, 2005, 2006), which also have been recorded in sediment cores around Puerto Rico and near the island (Woodruff et al., 2008; Malaize et al., 2011). Recent research in paleoclimate models indicates that the elevated SST generated by the MCA leads to bleaching and possible coral degradation (Declet-Perez et al., in prep.).

Methods

Excavation and material recuperation for Tierra Nuevas

The results presented in the section below are based on the zooarchaeological analysis of the vertebrate specimens from the site of Tierra Nuevas; the entire faunal assemblage was analyzed. However, this contribution focuses on the ichthyofauna to examine if changes in the exploitation and resource management pattern of marine ecosystems (e.g., corals) are related to landscape and climate change. The 2019 field expedition opened a 2x2m unit subdivided into four 1x1 units in mound E that followed natural stratigraphy subdivided into 5cm levels. All the materials were excavated and separated by type on the field. All the bones were collected from 4, and 2-mm sieves, and special features were collected as a whole and wet sieved. Charcoal samples were collected to produce the chronology and context of the units.

Zooarchaeology analysis

The faunal material was transported to the Museum National d'Histoire Naturelle in Paris to perform the osteologic and taxonomic identification using the reference collection available in the museum; guides and lists of local Caribbean species were consulted for double ID verification (Hildebrand, 1935; Humann & DeLoachm, 1989; Fishbase, 2019; Sea et al., 2011). Specimens were identified to the lowest taxonomic possible, including class, family, genus, and species identification. The data collection consisted of recording the number of individual specimens (NISP), identification element present, identification element side, identification element portion, measurements of identification element, and the minimum number of individuals (MNI) based on each specimen's identification element.

To document subsistence changes of past societies and understand faunal communities' response to paleoenvironmental change, we use ecological index, and size estimation to relate

taxonomic diversity. The dominance index (Glemarec, 1969) was used to identify the most relevant taxon in the sample by using the following equation: $IC = MA/M * 100$, in which MA is the NISP of the taxon, and M is the total number of the sample. These results allow us to identify which species are more present in the assemblage, indicating the fishing preferences of the indigenous people. The ecological index was measured using the Richness (S), Diversity (H'), Evenness (V'), and trophic level (TL), this index allows us to measure the environmental sustainability of the ecosystem. The Richness is equal to the number of taxons in the whole assemblage. For the Diversity, we used the Shannon-Weinner index with the following equation $H' = \sum(pi)\ (\log_{10} pi)$. Where H' refers to p_i is the relative abundance of the taxon "i" and log p_i refers to the logarithm of p_i (Shanon & Weinner, 1949). The interpretation of H's results is based on (Fernando et al., 1998), in which 3.5 and above represent very high diversity and 1.99 and below represent low diversity.

The evenness (Sheldon, 1969) was calculated using, $V' = H'/\log_e S$. In this case, H' is in the diversity index, and log sub e of cap S is the natural logarithm of the observed species number. Higher values of V' indicate a higher level of evenness, and lower values indicate that one of few species dominates the sample. To calculate the trophic level (TL) we use the values available on Fish Base and the adapted equation by Reitz (2004) $TL_{ij} = \sum(TL_{ij})(NISP_{ij})/\sum NISP_i$ in this case TL_{ij} is the TL of each taxon(j) by the period of time (i) multiplied by the NISP of the taxon (j) of that period (j). The result is divided by the sum of the NISP of that period. The diversity and evenness calculations were processed using Paleontological Statics (Past) data analysis software version 4.16C to process the large data set, avoid mathematical mistakes, and produce accurate results.

The fish size estimation was performed using the linear equation established by Grouard et al., 2019 and Jimenez-Cano, 2017, 2019 and Jimenez- Cano & Sierra Sosa, 2018 to examine the interrelations of exploitation according to a size that represents anthropogenic selections (Grouard et al., 2019). The measurements of specific bone elements were taken based on their robustness and potential recovery at archeological sites. Using as a guide the measurement points established by Grouard et al., 2019 and Jimenez-Cano, 2017, 2019 and Jimenez- Cano & Sierra Sosa, 2018 they were taken using Caliper (.01 mm), being very careful not to break the bones. For a list of all the linear equations and measurement points, we refer the reader to the annex Supplemental Table. 1 and Supplemental Table. 2. To evaluate the size estimation results of the same fishes throughout time in the assemblage, the Chi-square (X2) tests were undertaken using the Past 4.16C program to evaluate if the proportion of the sizes in each stratum is the same.

Results

A total of 14 charcoal samples were sent for analysis to the Keck Carbon Cycle AMS Facility of the Earth System Science Department at the University of Irvine (Supplemental figure 3.1). All results have been corrected for isotopic fractionation according to the conventions of Stuiver and Polach (1977), with $d^{13}C$ values measured on prepared graphite using the AMS spectrometer. These can differ from $d^{13}C$ of the original material and are not shown. The samples were treated with acid-base-acid (1N HCl and 1N NaOH, 75°C) prior to combustion. $d^{13}C$ values were measured to a precision of <0.1‰ relative to standards traceable to PDB, using a Thermo Finnigan Delta Plus stable isotope ratio mass spectrometer (IRMS) with Gas Bench input. Calibration was performed using the OxCal online platform using the IntCal20 curve. Table 3. 2 presents the depths and dates established for each stratum of the 2X2 m unit.

Table 3. 2 Stratums, depths, and Radiocarbon dates for the excavation unit at Tierras Nuevas.

Stratum	Depths	Date	Period
A	0-25 cm	Present	Present
B	25-35 cm	1400–1600 Cal CE	Late Ceramic Age to Contact
C	35-55 cm	1300-14000Cal CE	Late Ceramic Age
D/E	55-95 cm	800 – 950 Cal CE	Early Ceramic Age
F	95-100 cm	430-600 Cal CE	Early Ceramic Age
G	100-115 cm	2900 Cal BCE	

The sample presents an absence of dates between 950 and 1300 CE. This absence can be for a series of reasons: 1) only around 5% of the total archaeological site has been explored with excavation, meaning that mound E does not have activity during this time; 2) sampling methods location of the units do not cover the activity during this time or due to the activity in the site evidence of this time have been affected; 3) Possible reorganization of the society due to the changes in climate and hurricane impacts register during this time that affected the area.

Three main activity periods were identified and groped using the radiocarbon, stratigraphy, and faunal assemblage analyses (Table 3.2). By identifying this main period of events or site utilization occurring from stratum A to D, it is possible to investigate the changes in assemblage and ecosystem through time in correlation to the changes in the landscape and climate and the human selection of preference during those times. Stratum F and G do not contain any evidence of cultural material. Stratum F is associated with the batey floor from Plaza 2, and Stratum G constitutes the original surface before the habitation of Tierras Nuevas.

Table 3.2 Stratum organization

Stratum	Date
A (surface mix context)	Present
A (in context) & B	1400 & 1600 cal CE
C	1300 – 1400 cal CE
D & E (thin layer with a high density of materials inside stratum D evident in the western perfil)	800-950 cal CE

Assemblage description for Tierra Nuevas

A total of 16,123 vertebrate NISP representing 899 MNI was identified from Tierras Nuevas, with18 orders, 46 families, and 97 genre/families forming the assemblage (list of all the species Supplemental Table. 3). It is important to note that most fragments were micro fragments or unidentified pieces. The most abundant taxonomic group identified are the ray-finned fishes (Actinopterygii/Teleostei), followed by the mammals and testudines (Figure 3. 3). These three taxa together account for approximately 68% of all vertebrate taxonomic identification. Approximately 65% of the specimens identified as Actinopterygii were undiagnostic vertebrae or highly fragmented elements.

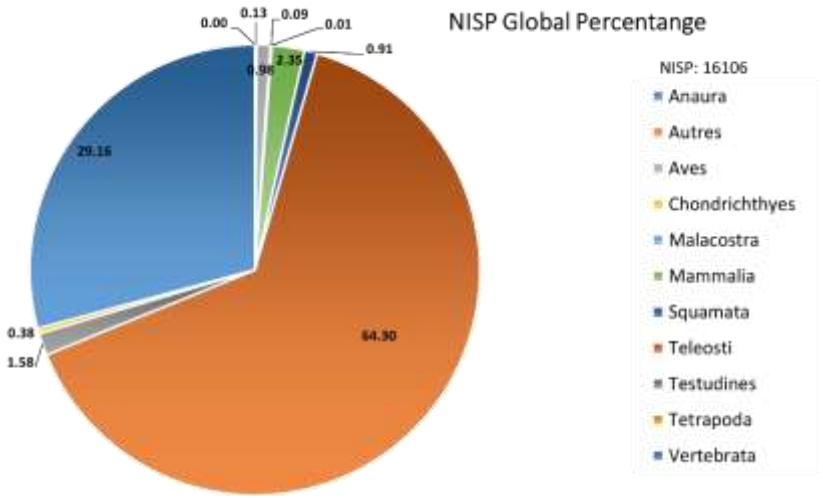

Figure 3. 3 Global Taxon NISP percentage identified in the Assemblage of Tierra Nuevas.

A total of 12 fish orders were identified, of which the Perciformes order is the most abundant, with the *Centropomus* sp. being the most representative in the sample (Figure 3. 4, top). Most fish species identified are associated with the coral reef, followed by brackish and open water (Figure 3. 4, bottom). However, it is important to remember that some fish species, like the *Ephinepelus* sp. and *Lutjanus* sp., are known to be associated with multiple environments throughout their life cycle, meaning that depending on their maturity stage, they can be found in different marine ecosystems.

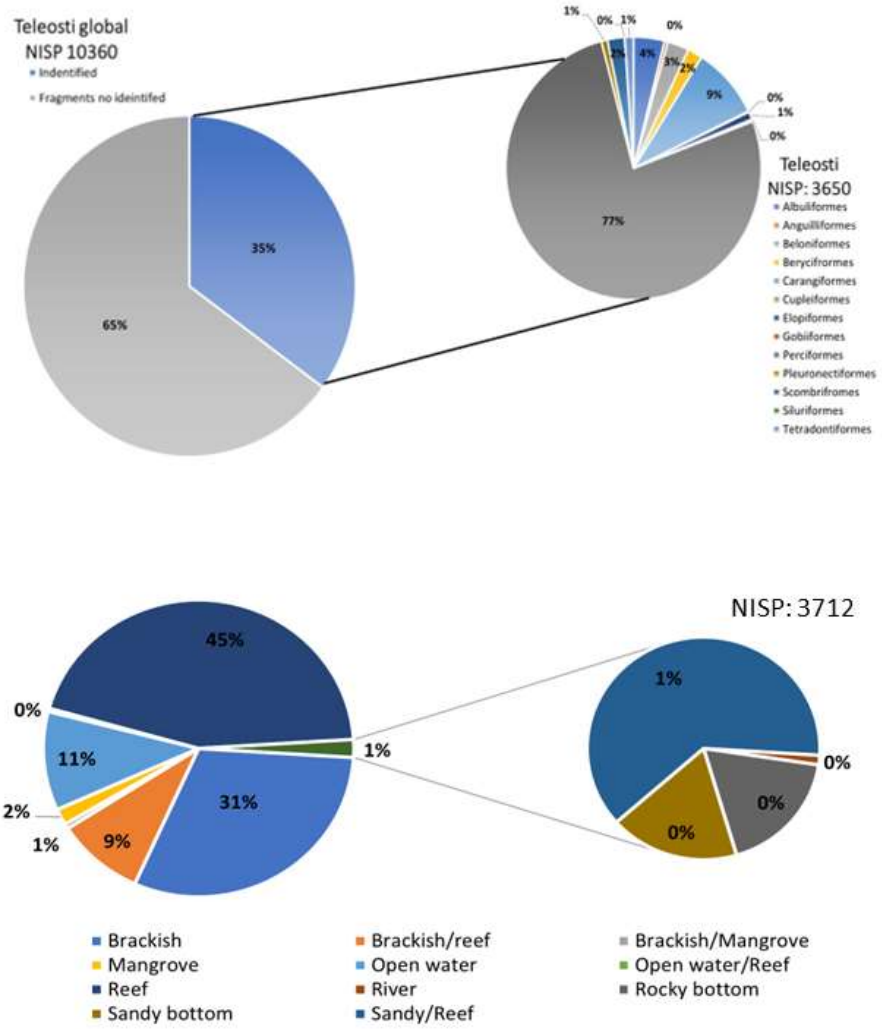

Figure 3. 4 The Global Teleostei assemblage is distributed by order (top graph) and ecosystem (bottom graph). The supplemental materials provide the full list of species.

Taxon distribution in the archaeological contexts

The taxon distribution in all the stratums and subunits presents the same pattern, with the Teleostei being the taxon with more presence, indicating a high selection of marine proteins over land proteins. It is important to note that unit N1005 E1208 was not fully excavated, so this unit only presents information on stratum A, B, and C.

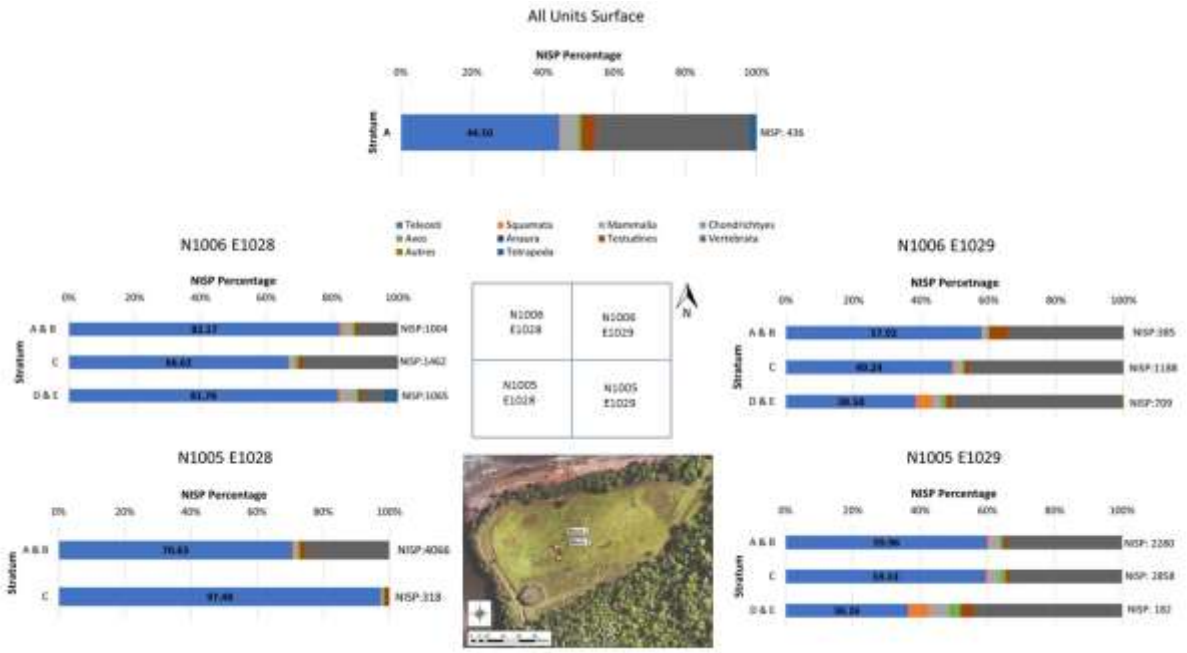

Figure 3. 5 Global percentage taxon distribution by units and stratum. The most predominant fish species in all the stratum are *Centropomus* sp., *Gerres* sp., *Haemulon* sp., and *Lutjanus* sp.

Ecological index

The ecological indices were calculated using the NISP as a quantifier in identification at the species level. Table 3. 3 summarizes the ecological index values calculated for the ichthyofauna of Tierras Nuevas.

Table 3. 3 Ecological indices per group stratum and global.

Index	Stratum A & B 1400-1900 CE	Stratum C 1300-1400CE	Stratum D & E 700-900CE	Global
Richness (S)	63	80	34	97
Diversity (H')	2.688	3.094	2.734	2.958
Evenness (V')	0.2333	0.2757	0.4528	0.1986

By applying these ecological indices by stratum group and overall, we observe that the ichthyofauna presents a high variability of species, as is seen in its richness values with a moderate diversity. These results indicate that the people used a gathering area representing a normal ecological community. However, if we look at that individually, Stratum C is the one that presents the highest diversity and richness. When evaluating the evenness, results indicate that the representation of the community in the sampler is less balanced. This is true for all stratum groups and the global index. This imbalance is visible in the predominance of the *Centropomus undecimalis*, *Centropomus parallelus*, *Centropomus ensiferus*, and *Centropomus* sp. (Centropomidae) throughout the entire sample (Figure 3. 6).

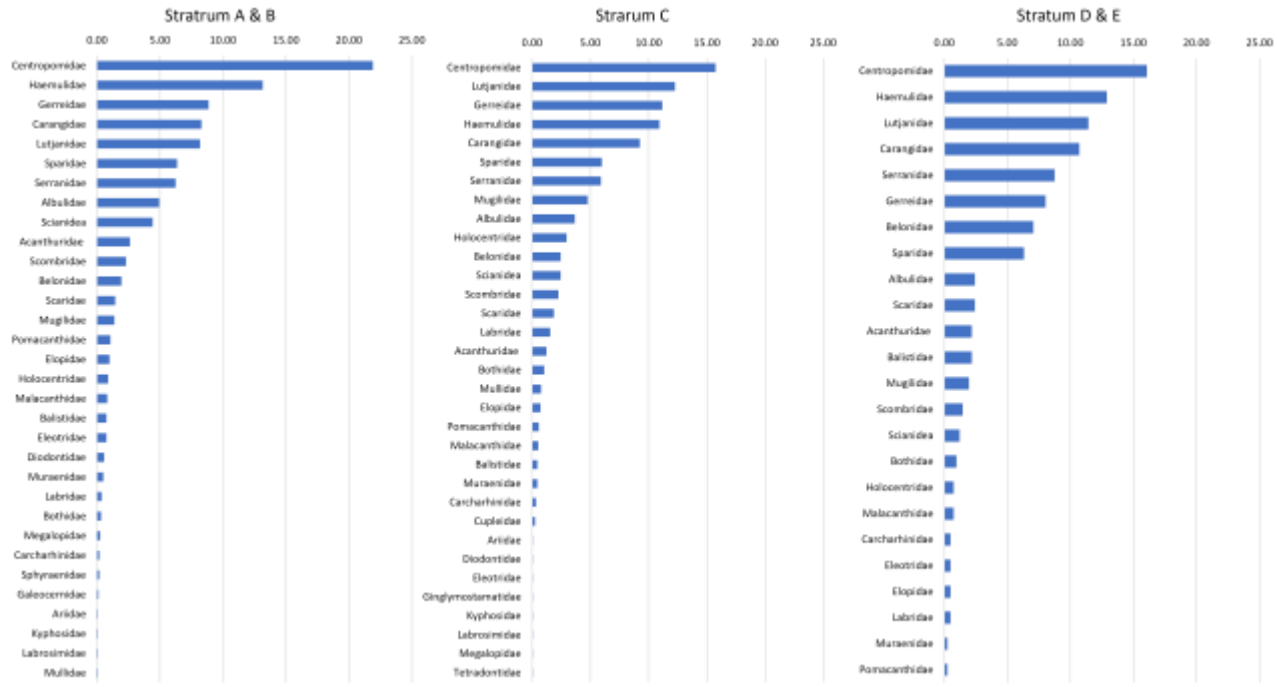

Figure 3. 6 Icthyofaunal family distribution by stratum. Sample dominance by species of the Centropomidae, Lutajanidae, and Haemulidae families.

The trophic levels in Tierra Nuevas indicate an ichthyofauna characterized as level 3 consumers composed mainly of fishes that are carnivores and omnivores in the three stratum groups Table 3. 4). The individual values for each period can be found in

Supplemental Table. 4. Even though the assemblage includes top predators such as sharks and tunas, their proportion is not high enough compared with secondary consumer species in the range of trophic level values of 3. In this case, the *Haemulon* sp. and *Lutjanus* sp. are the most dominant species. The herbivores represent 3.38% of the sample species, such as the *Mugil* sp. and *Sparisoma chrysopterum*, which are the least present in the assemblage, indicating a fishing preference for individual omnivores and carnivore fishes. The trophic levels results present a slight difference between strata, indicating that although there is a difference in the richness of species, the selection of the individuals continues to be towards moderate to high trophic levels fishes.

Table 3. 4 Trophic level per habitational period by stratum.

Period	Trophic level (TL)
Stratum A & B 1400-1900 CE	3.79
Stratum C 1300-1400CE	3.72
Stratum D & E 700-900CE	3.81
Global	3.76

Size Estimation

The fishes that were measured for the size estimation were the ones from the Centropomidae (*Centropomus* sp., *Centropomus undecimalis*) , Heamulidae (*Haemulon flavolineatum, Haemulon plumierii, Anisotremus* sp., *Conodon* sp., *Haemulon* sp.), and Serranidae (*Epinephelus guttatus*, *Epinephelus* sp., *Cephalopholis* sp., *Mycteroperca* sp.) families to have a representation of fishes that use the same marine ecosystem, in this case, the

coral reef and brackish water, and one family that, depending on the maturity stage of the fish can be found on the coral or brackish water.

According to the size estimation of the Centropomidae, Haemulidae, and Serranidae through the sample, it is possible to observe that the sizes for the three in a way behave similarly through time. In the case of the Haemulidae, most of the sample was caught between 120 mm to 259. mm of Standard Length (LS), the Serranidae between 120mm to 239 mm LS, and the Centropomidae between the120 mm to 259 mm LS. Figure 3. 7 indicates the mature length of the species in the green line, and the red line indicates the mean size of the caught fish, both of these measurements and in their total length (TL). The Haemulidae were caught mostly past the 120 mm to 179 mm range of their maturity length; the Centropomidae sample indicates they were caught before getting to the maturity states that occurs between 600 mm to 800 mm, and the Serranidae were caught in between their maturity length which occurs around 150 mm to 259 mm. The Centropomidae present a varied size range in the sample; however, few specimens surpass 500mm associated to *Centropomus undecimalis*.

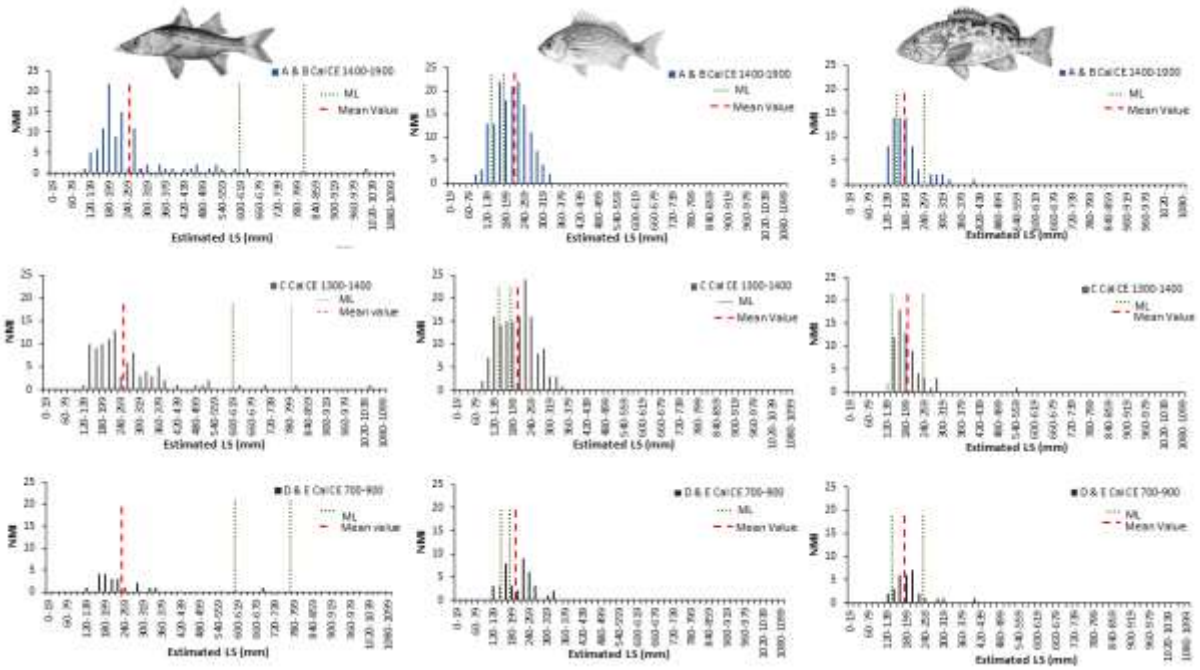

Figure 3. 7 Maximum standard length (LS, mm) size estimations in the Centropomidae, Haemulidae, and Serranidae families. Each panel represents the size of the family by the stratum organization.

Chi-square results indicate no significant difference between the size estimation of the Centropomidae and the Haemulidae; however, the Serranidae present significant differences between Stratum A & B and D & E (Table 3. 5). This difference could indicate a change in the availability of the species in the ecosystem in which it was caught. In this case, by the size predominance in D & E, it would have occurred in the shallow coral reef areas. These results indicate a tendency to catch fish in the same size range between 129 mm and 259 mm SL, suggesting the use of the same tools and fishing techniques in different environments.

Table 3. 5 Chi-Square test results for the size estimation of the Haemiludae, Serranidae, and Centropomidae.

	Haemulidae		Serranidae		Centropomidae	
	A & B	C	A & B	C	A & B	C
A & B						
C	X^2 = 3.8665 df. = 6 p= 0.69474		X^2 = 8.2056 df. = 6 p= 0.22343		X^2 = 11.658 df. = 15 p=0.7047	
D & E	X^2 = 3.627 df. = 6 p=0.72623	X^2 = 4.577 df. = 6 p= 0.59909	X^2 = 7.4589 df. = 6 p= 0.28048	X^2 = 2.8177 df. = 6 p= 0.83135	X^2 = 6.6011 df. = 15 p=0.96779	X^2 = 9.4814 df. = 15 p=0.85103

The difference between the layers is not significative at the probability of 0.2 or more, but = difference significative at the probability of 0.6 equals 60% of error; = difference significative at the probability of 0.3 equals 30% of error; = difference significative at the probability of 0.8 equals 80% of error.

The analysis of the faunal remains of the 2019 excavation follows the same pattern seen in a preliminary assessment performed by Grouard, in which she analyzed part of the sample from Davila's excavation (Hunt et al., 2013). In that case, a total of 130 NISP vertebrates were analyzed, of which the ray-finned fish were the most present, followed by mammalian. The order with the most representation was the Perciformes, in which the Centropomidae were the most present, consistent with the results presented here.

Angostura

The site of Angostura expands the zooarchaeological record of the floodplain of the Grande de Manatí River from a deeper time perspective by comparing the site of Tierras Nuevas. Angostura was excavated in 2008 by Rivera-Collazo (2011). The vertebrae analysis conducted by Yvonne Narganes and the invertebrate analysis by Isabel Rivera-Collazo (Narganes & Rivera-Collazo, 2011; Rivera-Collazo, 2011) allows assessing the ecological indexes at Angostura with the ones from Tierras Nuevas. When comparing the ecological indexes from Angostura and Tierras Nuevas, it is observed that Angostura presents lover values of richness and diversity (Table 3. 6). This could indicate that the selection of species and habitats is more specialized. However, the evenness index indicates a similar pattern as Tierras Nuevas, in which one or two

species dominate the sample. In this case, the sample is dominated by *Gobiomorus dormitor*, *Centropomus undecimalis,* and *Gerres cinereus*.

Table 3. 6 Tierras Nuevas and Angostura global ecological indices.

Index	Tierras Nuevas	Angostura
Richness (S)	97	16
Diversity (H')	2.958	1.105
Evenness (V')	0.1986	0.1888
Tropic Level	3.76	3.80

The low diversity of species in the Angostura sample is also reflected in the marine habitats. In Angostura, freshwater habitats are predominantly represented in the sample (Figure 3. 8). The analysis of the Angostura mollusk assemblage also supports the fish assemblage observation, showing that subsistence exploitation focused mostly on rivers (freshwater) resources, mangrove/estuarine, and riparian environments; some of the most abundant species were the *Anomalicardia brasiliana*, *Tagelus* spp, *Lucina pectinata* and *Neritina* spp. In contrast, the Tierras Nuevas sample presents more variation of habitats or species that use different habitats throughout their lifecycle, such as mangroves, seagrass sandy bottoms, coral reefs, and open water. The two habitats that dominate the Tierras Nuevas sample are reefs and brackish water.

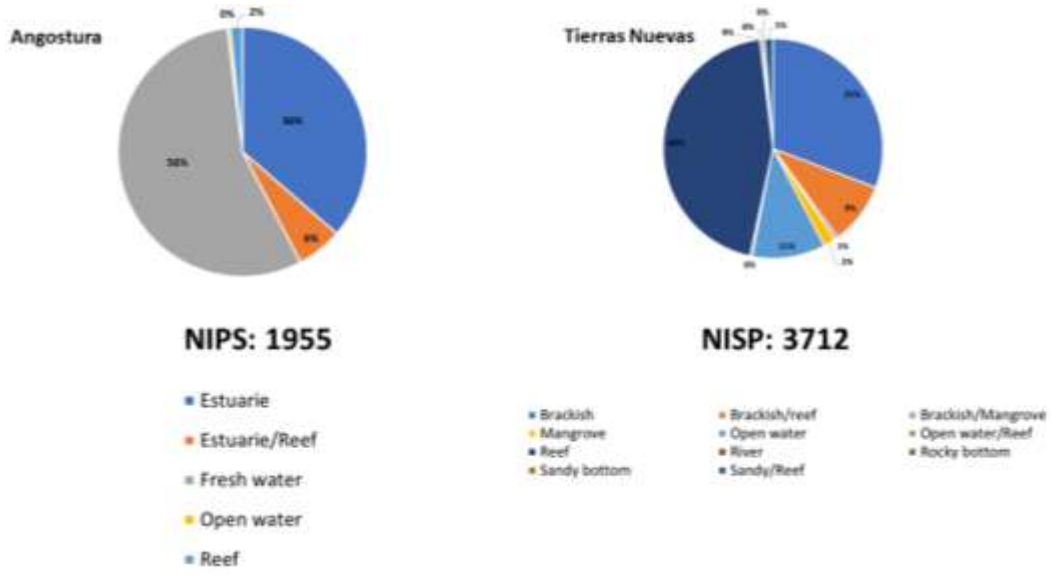

Figure 3. 8 Marine ecosystems in Angostura's ichthyofaunal sample (left) and Tierras Nuevas (right).

Discussion

The results of this analysis try to answer whether changes in the exploitation and resource management pattern of marine ecosystems (e.g., corals) are related to landscape and climate change. The first part of the discussion focuses on the Tierras Nuevas site; the second part compares with Angostura. Both archaeological sites fit the pattern observed in other sites of Puerto Rico and around the Caribbean basin, in which the faunal assemblage is mainly composed of fish remains, indicating the procurement of marine resources as gathering centers of proteins (Curet et al., 2006; Carlson & Steadman, 2009).

Tierras Nuevas

The site of Tierras Nuevas was established near the mangrove, coral reef, and riverine ecosystems during the mid-early ceramic age. The unit excavated during 2019 has three main strata of activity, with little variance between them in the assemblage. Using the ecological index allows us to start delimiting that variance between the strata. It is important to note that the earliest stratum does not contain materials because Stratum G marks the original sediments of the

site's formation, and Stratum F is part of the floor of Plaza 2. Meanwhile, Stratums D to A conforms Mound E on top of the north part of Plaza 2, indicating the extension of Plaza 2 under Mound E. During 700-900 cal CE, Stratum D was deposited, which contains a low quantity of fish species compared to the other stratum. During this time, the paleo landscape continued to present slow sediment accumulation that led to the beginning of the formation of the Tiburones marsh with a change in the river flow. In this stratum, the species that dominate the assemblage are *Centropomus undecimalis*, *Centropomus* sp., *Haemulon* sp., and *Lutajnidae* sp. being the most abundant *Centropomus* sp., indicating an exploitation of the brackish and coral reef areas.

900-1300 CE dates are absent, could be associated with changes in the activities occurring on the site, or can be related to climate change and hurricane activity effects as a result of the Medieval Climate Anomaly that occurred from around 800 to 1300 CE. Stratum C corresponds to the 1300 -1400 cal CE; during this time, the sediment accumulation led to an extension of the coastal plain, leaving a small estuary at the river mouth and shifting the boundaries of the Tiburones Marsh. Stratum C contains the highest number of fish species, presenting a slight change in species dominance during this time. The *Centropomus* sp. remains the dominant species, followed by the *Lutjanus* sp., *Gerres cinereus*, and *Gerres* sp. However, the ecosystem exploitation continues to be the same, with people predilecting brackish and coral reef areas as fishing areas. Stratum B & A is the second with the most fish species; *Centropomus* sp. remains the most representative in assemblage, followed by the *Haemulon* sp., *Gerres cinreus,* and *Gerres* sp. The same marine ecosystems continue to be predilected by the inhabitants of Tierras Nuevas.

The tropic level of each stratum and global unit indicates that the ichthyofaunal assemblage was dominated by carnivores and omnivore fishes with few great predators (ea.,

sharks). An important note when comparing the ichthyofauna present in the archaeological site and the current fish population in the region is that a similar spectrum of diversity and trophic level is still present around the site; however, they are low in frequency and quantity due to the current degradation of the coral reef and other coastal habitats in the north coastal region of Puerto Rico (Torres-Perez et al., 2021; Hernández-Delgado & Ortiz-Flores, 2022).

The size estimation performed for the individuals of the Centropomidae, Haemulidae, and Serranidae families in the assemblage indicates that the individuals captured were between the final juvenile stage and adulthood. As seen with the Haemulidae, the dominance of individuals past their maturity status indicates a conservation fishing method for the species associated with this family. This suggests that the *Haemulon plumieri*, *Haemulon flavolineatum*, *Haemulon carbonarium*, *Haemulon sciurus*, *Haemulon aurolineatum* and the *Anisotremus surinamensis* were caught directly in the coral reef. In this case, the population of Haemulidae in the coral reef near the site continues to be sustainable since the juvenile and immature fish population is not their main fishing target.

The Centropomidae and Serranidae present another scenario in which juvenile fishes are more present in the sample; in this case, juveniles tend to form schools that some large solitary individuals accompany; this behavior can be seen in the sample by the marked difference in the sizes and the presence of few adult individuals (Wallman, 2017; Grouard, 2001). The juvenile school fishes, especially the ones of the Centropomidae and Serranidae families, tend to live in brackish mangroves with some exceptions like the *Epinephelus guttatus* that tends to be found in coral beds and on the sandy and grassy bottoms of inshore areas, such as lagoons protected by coral reefs (Wallman, 2017; Grouard, 2001). The four species of Centropomidae found in the assemblage were caught in the brackish water near the site, near the mouth of the Grande River

of Manatí. The Serranidae also used brackish, mangrove, and reef bottom areas during their juvenile phase, indicating three areas for gathering the species found on the assemblage. Near the site of Tierras Nuevas are two main coral reef formations known as Machuca (currently degraded) and Tombolo reefs; these reefs could have been the provenance area for the coral reef ichthyofauna present in the site. Meanwhile, the brackish water is closer to the site because it is near the river mouth. The location of Tierras Nuevas on the coastline near the estuary, mangrove, and coral reef areas indicates the exploitation of local resources, meaning that the energy needed to capture the prey will be less than the ingested energy.

The size ranges in these three families also allow us to examine the fishing techniques pre-Columbian people used in Puerto Rico. Previous work on the island's east coast by Rivera-Collazo (2010) suggested using line-fishing and hooks; even though no fish hook was recovered in her work, the presence of high quantities of neritids suggests using them as a bite. Looking at the size estimation graphs for Tierras Nuevas and comparing them with ethnographic and ecology research on fishing methods, the archaeological assemblage curve follows the Gaussian curve size patterns formed by line fishing and hook methods (Millar, 1992). Gill nets are another fishing technique that allows fishing the same size and diversity of species. In this case, the twine diameter generates the base of the catching size. To further explore the use and size of gill nets in the archeological context, the consulted reference material must provide the diameter of the fish to construct future equations in which this variable can be calculated. When looking at contemporary fishing traditions on the same coastline, fishermen indicate that they continue to use the same areas where they were taught to fish and rotate between them to let the ecosystem recuperate; they even use similar techniques and tools as the indigenous people being their predilected hook and line, nets, and traps (Ojeda-Serrano at al., 2007).

Angostura also presents evidence of resource exploitation near their site, mostly of riverine and estuary/mangrove ecosystems. However, the landscape and climate conditions during the Angostura occupation differed from those during the occupation of Tierras Nuevas. The changes in the landscape are related to the changes in sea level and geomorphological response to sea level stabilization since the mid-Holocene. Research on sea-level change from the north and northwest of Puerto Rico has suggested a rise sea level maximum of -0.2±0.6 m at l,000 BCE (Khan et al., 2017); however, Rivera- Collazo (2011) found that the changes in the landscape in the study region are more associated with deposition within a fluvial-dominated system in a shallow marine basin under low tides regimes, typical of a landscape flooded during slow sea level rise that eventually became stable. The shift from slow sea rise towards stable levels in a fluvially dominated basin produced shoreline regression as depositional parameters that extended the delta seaward (Rivera-Collazo, 2011). These changes in sea level and landscape slowly transformed the ecosystem available for the past societies; the low transformation but continued presence of other marine ecosystems like the coral reef in the region indicates that harvesting practices were closer to the site rather than moving long distances to harvest.

The earliest habitational phase of Angostura indicates the use of the saline mangrove areas, as is suggested by the presence of the mollusk and the presence of the *Gobiomorus dormitor* and *Centropomus* sp., emphasizing the importance of the exploitation of river resources and mangrove/estuaries. The fish assemblage of the later habitational phase suggests habitat diversification with the incorporation of marine habitats (reefs and rocky shore). The changes seen in the habitat predominance reflect the changes seen in the paleo landscape, as discussed previously. The fish assemblage present on the site of Angostura suggests the use of traps and

cast nests for fishing, although hook and line could have been used to catch the *Caranx ruber* and *Megalops atlanticus* present in the assemblage.

The ichthyofauna from Angostura presents a marked difference from the habitat's predominance in Tierras Nuevas. Angostura presents a prevalence of freshwater fishes, followed by estuarine fauna; meanwhile, Tierras Nuevas presents a prevalence of brackish waters and coral reefs. This can be seen in the species predominance of each site. In Angosturas, the species with more presence are the *Gobiomorus dormitor* (Eleotridae), *Centropomus undecimalis* (Centropomidae), and *Gerres Cinereus* (Gerreidae). Whereas in Tierras Nuevas, the most prevalent species are Centropomus sp. (Centropomidae), Lutjanus sp. (Lutjanidae), and *Haemulon* sp. (Haemulidae). The ecological index for both sites indicates the preference of specific fish species in the assemblage even though it is diverse in both sites.

The habitats and ichthyofauna identified in Angostura matched the paleo landscape reconstruction made by Rivera-Collazo, in which the area presented riverine and estuary parameters. The assemblage presents species with mixed habitats, like the Serranidae and Lutjanidae; however, their presence in the sample is less than 5%. A revisit of the Angostura sample is suggested to expand the analysis and conduct bone measurements to see if the size of the caught fish follows the same pattern seen in Tierras Nuevas. By doing so, it could be confirmed the spectrum of fishing techniques, traditions, and sustainability in the region would be possible. The assemblage of Tierras Nuevas does not suggest signs of overexploitation of the ecosystems since the species and the use of the same marine ecosystems are continuous on the sample, and the size estimation does not show differences between strata. However, when looking at the *Centropomus* sp., especially the *Centropomus undecimalis*, which is the constant species from Angostura to Tierras Nuevas, a measurement assessment is needed from the

Angostura sample to see if the sizes predominant in Tierras Nuevas indicate overexploitation of this specie or human predilection. During the summer of 2023, four 1x1 m^2 units were opened in other areas of the Tierras Nuevas site; faunal analysis and radiocarbon dating will be performed to expand the database of the current results and will be published in a separate report.

Conclusion

The work investigated if changes in paleolandscape and climate cloud have affected the marine resources available for the pre-Columbian communities and how people responded to the changes. Comparing the sites of Tierras Nuevas and Angostura presents a unique opportunity to understand local changes on the north coast of Puerto Rico, as both sites are located in the same area of the Grande the Manatí River and are separated only by approximately 3.6 km. The continuous utilization of the region since the 4010 BCE (5960 +/- 250 uncalibrated) Angostura up to 1600 cal 95% AD in Tierras Nuevas provides data on the deep-time interactions between the societies and the marine ecosystem. The data also shed light on the possible fishing techniques implemented by the past societies in the region.

As the landscape changes slowly near the site areas, the fish assemblage indicates the use of developing or already established ecosystems near the sites, like the coral reef towards the north coastline of Tierras Nuevas. The high presence of coral reef fish in the Tierra Nuevas site indicates the exploitation of the nearby ecosystem since the reef is in front of it. During the occupation of Angostura, the coral reef was more distant from the site than the mangrove and river. Tierras Nuevas's species and size estimation confirm the tendency to use brackish water, coral reefs, and inshore areas like seagrass beds as their main fishing areas. These ecosystems serve as homes and nurseries of juvenile fishes that are more representative of the ichthyofauna assemblage of Tierras Nuevas. The site of Angostura presents a diversification in the ecosystems

represented in the sample in the later occupation phase, in which fishes are included in addition to the mangrove/riverine. Angostura presents the same pattern of local resource exploitation near the site as seen Tierras Nuevas.

The continued presence of the Centropomidae family since the early inhabitants and the size estimation performed on the Tierras Nuevas sample indicated the continued exploitation of the same resource throughout time, indicating that even the changes that occurred in the landscape do not affect the resource availability and the human selection. The size estimation performed in this analysis does not shed light on resource overexploitation in Tierres Nuevas. Paleoclimate models already indicate the possibility of coral bleaching and hurricanes affecting the region during the Medieval Climate Anomaly, and the site of Tibes, in the south coast of Puerto Rico, shows changes after a hurricane affected the region; however, further research is needed from the 2023 field season to corroborate the date gap seen form 900-1300 CE in Tierras Nuevas to assess if it is related to climate factors or human decision process.

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SUPPLEMENTAL TABLES

Supplemental Table. 1 Fish size equations for Haemulidae and Serranidae. (From Grouard et al., 2019).

Measurement Point	Taxon	Equation	Y=	A	X+	B	R^2=
	Haemulidae						
Articular M2	*Haemulon* sp.	Y=41.693(x)+48.279	Y=	44.693	X+	48.279	.7918
Articular M2	*Conodon* sp.	Y=56.585(x)+22.597	Y=	56.585	X+	22.597	.927
Articular M2	*Anisotremus* sp.	Y=16.754(x)+127.43	Y=	16.754	X+	127.43	.632
Maxillary M1	*Haemulon* sp.	Y=36.834(x)+61.45	Y=	36.834	X+	61.45	.8685
Maxillary M1	*Anisotremus* sp.	Y=30.892(x)+97.848	Y=	30.892	X+	97.848	.8434
Premaxillary M1	Haemulidae	Y=34.772(x)+89.83	Y=	34.772	X+	89.83	.6816
Premaxillary M2	*Haemulon* sp.	Y=9.5458(x)+54.886	Y=	9.5458	X+	54.886	.8429
Premaxillary M2	*Conodon* sp.	Y=17.856(x)+58.594	Y=	17.856	X+	58.594	.6659
Premaxillary M1	*Anisotremus* sp.	Y=55.18(x)+33.071	Y=	55.18	X+	33.071	.7504
Vomer	Haemulidae	Y=20.781(x)+46.802	Y=	20.781	X+	46.802	.6359
Vomer	*Anisotremus* sp.	Y=21.533(x)+59.715	Y=	21.533	X+	59.715	.6156
Dentary M1	Haemulidae	Y=15.358(x)+100.77	Y=	15.358	X+	100.77	.6252
Dentary M1	*Haemulon* sp.	Y=19.983(x)+64.006	Y=	19.983	X+	64.006	.8359
Dentary M2	*Anisotremus* sp.	Y=29.065(x)+63.318	Y=	29.065	X+	63.318	.6602
Quadrate M1	*Haemulon plumieri*	Y=32.858(x)+39.487	Y=	32.858	X+	39.487	.8338
Quadrate M1	*Haemulon* sp.	Y=31.758(x)+45.434	Y=	31.758	X+	45.434	.8764
VPC1 M1	*Haemulon* sp.	Y=26.061(x)+70.294	Y=	26.061	X+	70.294	.8694
VPC1 M2	*Haemulon flavolineatum*	Y=27.925(x)+78.859	Y=	27.925	X+	78.859	.9486
VPC1 M1	*Anisotremus* sp.	Y=29.853(x)+35.194	Y=	29.853	X+	35.194	.8954
PC toraxic M3	*Haemulon flavolineatun*	Y=25.734(x)+44.78	Y=	25.734	X+	44.78	.971
PC toraxic M2	*Haemulon* sp.	Y=31.525(x)+66.351	Y=	33.525	X+	66.351	.8779
PC toraxic M3	*Conodon* sp.	Y=29.961(x)+24.318	Y=	29.961	X+	24.318	.9641
PC toraxic M2	*Anisotremus* sp.	Y=34.521(x)+37.094	Y=	34.521	X+	37.094	.8976
PC toraxic M3	Haemulidae	Y=32.723(x)+15.873	Y=	32.723	X+	15.873	.8769
VC1 M3	*Haemulon* sp.	Y=31.639(x)+21.872	Y=	31.639	X+	21.872	.8784
VC1 M2	*Anisotremis* sp.	Y=25.422(x)+87.266	Y=	25.422	X+	87.266	.8569
VC1 M3	Haemulidae	Y=32.554(x)+15.414	Y=	32.554	X+	15.414	.8982
VC10 M2	*Haemulon* sp.	Y=36.772(x)+57.898	Y=	36.772	X+	57.898	.88
VC10 M2	Haemulidae	Y=37.782(x)+52.045	Y=	37.782	X+	52.045	.8859
Measurement Point	Taxon	Equation	Y=	A	X+	B	R^2=
	Serranidae						
Articular M1	Epinephelus sp.	Y=38.812(x)+34.872	Y=	38.812	X+	34.872	.9727
Articular M1	Serranidae	Y=40.001(x)+30.559	Y=	40.001	X+	30.559	.9652
Maxillary M2	*Epinephelus* sp.	Y=31.288(x)+10.392	Y=	31.288	X+	10.392	.9645

Continuation Supplemental table.1 Fish size equations for Haemulidae and Serranidae. (From Grouard et al., 2019).

Maxillary M3	*Cephalopolis* sp.	Y=24.497(x)+45.551	Y=	24.497	X+	45.551	.7875
Maxillary M1	Serranidae	Y=74.726(x)+49.224	Y=	74.726	X+	49.224	.9456
Premaxillary M3	*Epinephelus guttatus*	Y=33.781(x)+14.066	Y=	33.781	X+	14.066	.9159
Premaxillary M3	*Epinephelus* sp.	Y=34.778(x)+11.21	Y=	34.778	X+	11.21	.9763
Premaxillary M2	*Cephalopolis* sp.	Y=15.712(x)+42.397	Y=	15.712	X+	42.397	.7162
Premaxillary M2	*Mycteroperca* sp.	Y=23.547(x)+3.5283	Y=	23.547	X+	3.5283	.9945
Premaxillary M3	Serranidae	Y=28.993(x)+9.7323	Y=	28.993	X+	9.7323	.9531
Vomer	*Epinephelus* sp.	Y=28.487(x)+24.225	Y=	28.487	X+	28.487	.9615
Vomer	Serranidae	Y=21.533(x)+59.715	Y=	21.533	X+	59.715	.9531
Dentary M1	*Epinephelus guttatus*	Y=32.445(x)+61.053	Y=	32.445	X+	61.053	.8998
Dentary M1	Epinephelus sp.	Y=34.759(x)+52.035	Y=	34.759	X+	52.035	.9644
Dentary M1	*Cephalopholis* sp.	Y=25.353(x)+68.586	Y=	25.353	X+	68.586	.7457
Dentary M1	Epinephelinae	Y=32.476(x)+50.447	Y=	32.476	X+	50.447	.9517
Dentary M1	Serranidae	Y=31.897(x)+58.459	Y=	31.897	X+	58.459	.9437
Quadrate M1	Epinephelus sp.	Y=42.281(x)+46.559	Y=	42.281	X+	46.559	.9768
Quadrate M2	*Cephalopholis* sp.	Y=76.399(x)+37.324	Y=	76.399	X+	37.324	.815
Quadrate M1	Serranidae	Y=43.202(x)+35.652	Y=	43.202	X+	35.652	.9742
VPC1 M2	*Epinephelus guttatus*	Y=32.979(x)+59.836	Y=	26.061	X+	70.294	.9296
VPC1 M3	Epinephelus sp.	Y=45.424(x)+24.623	Y=	27.925	X+	78.859	.9787
VPC1 M2	*Cephalopholis* sp.	Y=39.675(x)+42.601	Y=	29.853	X+	35.194	.8241
VPC3 M1	Epinephelus sp.	Y=35.12(x)+55.111	Y=	35.12	X+	55.111	.9791
VPC3 M1	*Cephalopholis* sp.	Y=40.593(x)+31.841	Y=	40.593	X+	31.841	.8547
VPC3 M1	Serranidae	Y=37.076(x)+40.383	Y=	37.076	X+	40.383	.9821
VPC7 M1	Epinephelus sp.	Y=34.78(x)+46.367	Y=	34.78	X+	46.367	.9838
VPC7 M1	*Cephalopholis* sp.	Y=38.572(x)+29.292	Y=	38.572	X+	29.292	.9032
VPC7 M1	Serranidae	Y=35.314(x)+43.948	Y=	35.314	X+	43.948	.9809
VPC	Serranidae	Y=35.477(x)+44.406	Y=	35.477	X+	44.406	.9759
VC M1	Serranidae	Y=35.291(x)+52.81	Y=	35.291	X+	52.81	.9549
VC8 M1	Epinephelus sp.	Y=37.847(x)+70.221	Y=	37.847	X+	70.221	.9721
VC8 M1	*Cephalopholis* sp.	Y=38.479(x)+6.4522	Y=	38.479	X+	6.4522	.9312
VC8 M3	Serranidae	Y=38.292(x)+53.112	Y=	38.292	X+	53.112	.9637
V M1	Serranidae	Y=35.365(x)+47.994	Y=	35.365	X+	47.994	.9665

Supplemental Table. 2 Fish size equations for Centropimidae. (From Jimenez-Cano, 2017, 2019 and Jimenez- Cano & Sierra Sosa, 2018)

Measurements Points	Taxon	Equation	Y=	A	X+	B	R^2=
	Centropomidae						
Articular	Centropomidae	Y=44.514(x)+38.014	Y=	44.514	X+	38.014	.9981
Vomer	Centropomidae	Y=1.1178(x)+1.7034	Y=	1.1178	X+	1.7034	.9417
Dentary	Centropomidae	Y=0.9604(x)+1.1812	Y=	0.9604	X+	1.1812	.9472
VPC1 M1	Centropomidae	Y=44.514(x)+39.014	Y=	44.514	X+	39.014	.9981
VPC "ce" M1	Centropomidae	Y=41.647(x)+38.461	Y=	41.647	X+	38.461	.923
VPC "th" M1	Centropomidae	Y=33.973(x)+46.126	Y=	33.973	X+	46.126	.9735
VC M3	Centropomidae	Y=33.471(x)+16.807	Y=	33.471	X+	16.807	.9839

Supplemental Table. 3 List of Species with NISP and NMI grouped by stratum.

Class	**Order**	**Genre/Specie**	**Starum A & B**		**Stratum C**		**Stratum D & E**	
			NISP	**NMI**	**NISP**	**NMI**	**NISP**	**NMI**
Tetrapod			9		1259		47	
Vertebrata			2,299		1901		502	
Mammal			162	13	28		8	
	Primates							
		Homo Sapiens	3	1	7		8	
	Rodentia		47	11	76	19	16	6
		cf. *Cavia* sp.			3	2		
		cf. Cavidae	2					
		Isolobodon portoricensis	4		23	2		
		cf. *Isolobodon portoricensis*	68	1	5		21	
Bird								
	Bird							
		Bird	59	9	74	22	23	4
Squamata								
	Iguanidae		3		1	1	3	
	Serpentes							
		Chilabothrus inoratus	5	2	1		2	1
		Boidae			1			
		Borikenophis portoricensis	38		19		49	
		Colubridae	3		10			
Testudines								
	Emydidae		139	4	72	1	33	2
		Trachemys sp.			4		1	
	Chelonoidae		1				**1**	

Continuation Supplemental Table 3. List of Species with NISP and NMI grouped by stratum.

Amphibia								
	Anura		1	1			1	1
Chondrichthyes								
	Orectolobiformes							
		Ginglymostoma cirratum			1	1		
	Carcharhiniformes							
		Negaprion brevirostris					1	1
		Galeocerdo cuvier	2	1				
		Carcharhinidae	3		5		1	
	Myliobatiformes						1	1
Ostheichthyes								
	Elopiformes							
		Elops saurus	16		11		2	
		Megalops atlanticus	4		1			
		cf. Megalopidae	1					
	Albuliformes							
		Albula vulpes	79		57	2	10	1
	Anguiliformes							
		Gymnothorax sp.	8		4		1	
		cf. *Gymnothorax*			3			
	Clupeiformes							
		cf. *Harengula* sp.			4			
	Siluriformes							
		Sciades props	1	1	1			
	Holocentriformes							
		Holocentrus sp.	6		39	14	3	1
		cf. *Holocentrus* sp.			1			
		Holocentrus cf. *adscensionis*			1			
		Holocentridae	8		5	1		
		cf. Holocentridae	3		5		1	
	Scombriformes							
		Scomberomorus sp.	1	1	2	1		
		Thunnus cf. atlanticus			7			
		Thunnus sp.	20	1	16	1	2	
		cf. *Thunnus* sp.	4	2	4		1	
		Euthynnus alletteratus	4					
		Scombridae	8		6		3	
		cf. Scombridae	1					
	Mulliformes							
		Mulloidichthys martinicus	1		2	1		

Continuation Supplemtal Table. 3 List of Species with NISP and NMI grouped by stratum.

		Mulloidichthys cf. *martinicus*			5			
		cf. *Pseudupeneus maculatus*			1	1		
		Mullidae			4			
	Gobiiformes							
		Eleotris pisonis	12		1		2	
	Carangia/misc							
		Centropomus undecimalis			2			
		Centropomus parallelus	2	2	7	2		
		Centropomus cf. *parallelus*			2	2		
		Centropomus ensiferus			10	2		
		Centropomus cf. *ensiferus*			1	1		
		Centropomus sp.	350	50	223	30	66	14
		cf. *Centropomus* sp.	12		1		4	
		Sphyraena sp.	3					
	Pleuronectiformes							
		Botuhs sp.	8		16		6	
	Carangiformes							
		Caranx hippos			3	2		
		Caranx cf. *hippos*	1	1	1	1		
		Caranx cf. *ruber*	4					
		Caranx bartholomaei			2	1		
		Caranx cf. *bartholomaei*	2	1				
		Caranx sp.	70	2	71	3	29	
		cf. *Caranx* sp.	1		23		1	
		Selene vomer	1		4	3		
		Decapterus sp.	3		20		8	
		cf. *Decapterus* sp.	2					
		cf. *Seriola* sp.	1	1	2			
		Trachinotus sp.	1				1	
		cf. *Trachinotus* sp.	2				1	
		Carangidae	45	1	19	3	4	1
		cf. Carangidae	1					
	Beloniformes							
		Strongylura sp.						
		cf. *Strongylura* sp.	28		11	1	23	
		Tylosurus crocodilus			4			
		Tylosurus sp.	1		5			
		cf. *Tylosurus* sp	2		16	1	6	
		Belonidae			2	1		
	Mugiliformes							

Continuation Supplemental Table.3 List of Species with NISP and NMI grouped by stratum.

		Mugil sp.	22		56	3	8	
		cf. *Mugil* sp.			7			
		Mugilidae			11			
	Bleniiforemes							
		Labrisomus nuchipinnis	1	1	1	1		
	Acanthuriformes							
		Holacantus sp.	17		7		1	
		Pomacanthus sp.			1	1		
		Pomacanthidae			1			
		Acanthurus sp.	41	3	13	1	9	1
		cf. *Acanthurus* sp.			6	1		
		Acanthuridae	1					
		cf. Acanthuridae	1		1			
	Tetraodontiformes				1			
		Balistes sp.	3	1				
		Balistidae	9	1	7	2	9	2
		Diodon sp.	3	1				
		cf. *Diodon* sp.	6					
		Chilomycterus sp.			1			
	Centrarchiformes							
		Khyposus sp.	1	1	1	2		
	Eupecaria/misc							
		Heteropricanthus cruentatus			1	1		
		Malacanthus plumieri	13		8		3	
		cf. Malacanthidae	1					
		Lutjanus apodus			1			
		Lutjanus cf. *apodus*			1		1	1
		Lutjanus buccanella			2			
		Lutjanus cf. *buccanella*			3	1		
		Lutjanus vivanus	1	1	5	1	2	1
		Lutjanus cf. *vivanus*	8	2	2			
		Lutjanus cf. *campechanus*			1			
		Lutjanus sp.	119	17	131	14	38	7
		cf. *Lutjanus* sp.			17	4		
		Ocyurus chrysurus	5		11	1	4	1
		cf. *Ocyurus chrysurus*	3		3		1	
		Rhomboplites aurorubens	1		3	2		
		Rhomboplites cf. *aurorubens*			2	2		
		Etelis cf. *oculatus*			1	1		
		Lutjanidae	1		6	4	1	1

Continuation Supplemental Table.3 List of Species with NISP and NMI grouped by stratum.

		cf. Lutjanidae	4		1	1		
		Gerres cinereus	2		17	7		
		Gerres cf. *cinereus*	1		5	1		
		Gerres plumieri			1		1	
		Gerres cf. *plumieri*			1			
		Gerres sp.	120	20	113	16	25	
		cf. *Gerres* sp.			17	3	7	
		Gerreidae	9		14	2		
		cf. Gerreidae	5	1				
		Diapterus auratus	7	1	5			
		Diapterus sp.	3		1			
		Haemulon cf. *plumieri*	2					
		Haemulon cf. *sciurus*			1			
		Haemulon flavolineatum			2	7		
		Haemulon cf. *flavolineatum*			3			
		Haemulon aurolineatum			2		1	
		Haemulon cf. *aurolineatum*	2				1	
		Haemulon carbonarium	2		3	2		
		Haemulon sp.	166	14	134	3	43	5
		cf. *Haemulon* sp.			5			
		Conodon nobilis	4	1	3	1		
		Anisotremus cf. *virginecus*			1	1		
		Anisotremus suranimensis			7			
		Anisotremus cf. *suranimensis*	2	1				
		Anisotremus sp.	14	7	3		2	
		cf. *Anisotrenus* sp.			3	2		
		Haemulidae	19	5	3	1	5	
		cf. Haemulidae	14		3		2	
		Rhonciscus crocro					1	
		Archosargus rhomboidalis	1		3		3	
		Archosargus cf. *rhomboidalis*			9			
		cf. *Archosargus* sp.			4			
		Calamus calamus	5					
		Calamus sp.	6		15		6	
		cf. *Calamus* sp.	3		8		3	
		Sparidae	87	1	54		13	
		Sciaenops sp.			3	1		

Continuation Supplemental Table.3 List of Species with NISP and NMI grouped by stratum.

		cf. Sciaenops sp.	4		3			
		cf. E*quetus* sp.					1	1
		Umbrina sp.	1	1				
		cf. *Umbrina* sp.					1	
		Micropogonias furnieri	2	2	5	4		
		Micropogonias sp.	2	1				
		Bairdiella ronchus			1	1		
		Bairdiella cf. *ronchus*	1	1	1	1		
		Pareques cf. *acuminatus*			1	1		
		cf. *Pareques*			1	1		
		Sciaenidae	61	5	25	3	3	1
		Bodianus rufus			1			
		Bodianus cf. *rufus*			1	1		
		Bodianus sp.	1				1	
		cf. *Bodianus* sp.			1			
		Halichoeres sp.	1	1				
		Labridae	4		1	1		
		Scarus sp.	6	1	9	5	1	1
		cf. *Scarus* sp.						
		Saprisoma cf. *chrysopterum*	2	1	1	2		
		Sparisoma sp.	9	4	6	1	7	2
		cf. *Sparisoma* sp.			1			
		Scaridae	6	2	12	2	2	
	Perciformes/ Serranoide							
		Epinephelus guttatus			1	1	2	1
		Epinephelus cf. *guttatus*			2	1	1	
		Epinephelus sp.	12	6	19	3	9	3
		cf. *Epinephelus* sp.	14	3	13	3	4	
		Mycteroperca sp.	1	1	1			
		cf. *Mycteroperca* sp.			1			
		Cephalopholis cf. *fulva*			1			
		Cephalopolis sp.	6	3	5	1	3	1
		cf. *Cephalopolis* sp.	2	1	5	1	1	1
		Serranidae	65	12	44	3	16	3
		cf. Serranidae	4	1	3			
	Perciformes				2	1		
	Teleostei		3,848		1,994	13	724	

Supplemental Table. 4 Trophic level values for all the identified fish species. Trophic level values from the fish base database.

Taxa	TL	Starum A & B		Startum C		Stratum D & E		Total	
		NISP	TLij	NISP	TLij	NISP	TLij	NISP	TLij
Ginglymostoma cirratum	4.2			1	4.2			1	4.2
Negaprion brevirostris	4.3					1	4.3	1	4.3
Galeocerdo cuvier	4.5	1	4.5					1	4.5
Elops saurus	3.5	16	56	11	38.5	2	7	29	101.5
Megalops atlanticus	4.5	4	18	1	4.5			5	22.5
Albula vulpes	3.7	79	292.3	57	210.9	10	37	146	540.2
Gymnothorax sp.	4	8	32	4	16	1	4	13	52
cf. *Gymnothorax*	4			3	12			3	12
cf. *Harengula* sp.	3.3			4	13.2			4	13.2
Sciades proops	4.4	1	4.4	1	4.4			2	8.8
Holocentrus sp.	3.1	6	18.6	39	120.9	3	9.3	48	148.8
cf. *Holocentrus* sp.	3.1			1	3.1			1	3.1
Holocentrus cf. *adscensionis*	3.1			1	3.1			1	3.1
Scomberomorus sp.	4.5	1	4.5	2	9			3	13.5
Thunnus cf. *atlanticus*	4.3			7	30.8			7	30.8
Thunnus sp.	4.3	20	86	16	68.8	2	8.6	38	163.4
cf. *Thunnus* sp.	4.3	4	17.2	4	17.2	1	4.3	9	38.7
Ethynnus alletteratus	4.5	4	18					4	18
Mulloidichthys martinicus	3.2	1	3.2	2	6.4			3	9.6
Mulloidichthys cf. *martinicus*	3.2			5	16			5	16
cf. *Pseudupeneus maculatus*	3.7			1	3.7			1	3.7
Eleotris pisonis	3.7	12	44.4	1	3.7	2	7.4	15	55.5
Centropomus undecimalis	4.2			2	8.4			2	8.4
Centropomus parallelus	4.2	2	8.4	7	29.4			9	37.8
Centropomus cf. *parallelus*	4.2			2	8.2			2	8.2
Centropomus ensiferus	4.2			10	42			10	42
Centropomus cf. *ensiferus*	4.2			1	4.2			1	4.2
Centropomus sp.	4.2	350	1470	223	936.6	66	277.2	639	2683.8
cf. *Centropomus* sp.	4.2	12	50.2	1	4.2	4	16.8	17	71.2
Sphyraena sp.	4.4	3	4.4					3	4.4
Bothus sp.	4.5	8	36	16	70.4	6	17.6	30	124
Caranx hippos	3.6			3	10.8			3	10.8
Caranx cf. *hippos*	3.6	1	3.6	1	3.6			1	3.6

Supplemental Table. 4 Trophic level values for all the identified fish species. Trophic level values from the fish base database.

Caranx cf. *ruber*	4.3	4	17.2					4	17.2
Caranx bartholomaei	4.5			2	9			2	9
Caranx cf. *bartholomaei*	4.5	2	9					2	9
Caranx sp.	4.05	70	283.3	71	287.55	29	117.45	170	688.3
cf. *Caranx* sp.	4.05	1	4.05	23	93.15	1	4.05	25	101.25
Selene vomer	4.3	1	4.3	4	17.2			5	21.5
Decapterus sp.	4	3	12	20	80	8	32	31	124
cf. *Decapterus* sp.	4	2	8					2	8
cf. *Seriola* sp.	4.5	1	4.5	2	9			3	13.5
Trachinotus sp.	4	1	4			1	4	2	8
cf. *Trachinotus* sp.	4	2	8			1	4	3	12
Strongylura sp.	4.4								
cf. *Strongylura* sp.	4.4	28	123.2	11	48.4	23	101.2	62	272.8
Tylosurus crocodilus	4.5			4	17.6			4	17.6
Tylosurus sp.	4.5	1	4.5	5	22.5			6	27
cf. *Tylosurus* sp	4.5	2	9	16	72	6	27	24	108
Mugil sp.	2.5	22	55	56	140	8	20	86	215
cf. *Mugil* sp.	2.5			7	17.5			7	17.5
Labrisomus nuchipinnis	3.6	1	3.6	1	3.6			2	7.2
Holacantus sp.	3	17	51	7	21	1	3	25	75
Pomacanthus sp.	3			1	3			1	3
Acanthurus sp.	2.2	41	90.2	13	28.6	9	19.8	63	138.6
cf. *Acanthurus* sp.	2.2			6	13.2			6	13.2
Balistes sp.	3.8	3	11.4					3	11.4
Diodon sp.	3.9	3	11.7					3	11.7
cf. *Diodon* sp.	3.9	6	23.4					6	23.4
Chilomycterus sp.	3.8			1	3.8			1	3.8
Khyposus sp.	2	1	2	1	2			2	4
Heteropriacanthus cruentatus	3.6			1	3.6			1	3.6
Malacanthus plumieri	3.7	13	48.1	8	29.6	3	11.1	24	88.8
Lutjanus apodus	4.3			1	4.3			1	4.3
Lutjanus cf. *apodus*	4.3			1	4.3	1	4.3	2	8.6
Lutajnus buccanella	3.9			2	7.8			2	7.8
Lutjanus cf. *buccanella*	3.9			3	11.7			3	11.7
Lutjanus vivanus	3.1	1	3.1	5	15.5	2	3.1	7	21.7
Lutjanus cf. *vivanus*	3.1	8	24.8	3	9.3			11	34.1
Lutjanus sp.	4	119	476	131	524	38	152	288	1152
cf. *Lutjanus* sp.	4			17	68			17	68
Ocyurus chrysurus	4	5	20	11	44	4	16	20	80
cf. *Ocyurus chrysurus*	4	3	12	3	12	1	4	7	28

Supplemental Table. 4 Trophic level values for all the identified fish species. Trophic level values from the fish base database.

Rhomboplites aurorubens	4.4	1	4.4	3	13.2			4	17.6
Rhomboplites cf. *aurorubens*	4.4			2	8.8			2	8.8
Etelis cf. *oculatus*	4.2			1	4.2			1	4.2
Gerres cinereus	3.5	2	7	17	59.5			19	108.5
Gerres cf. *cinereus*	3.5	1	3.5	5	17.5			4	52.5
Gerres plumieri	2.2			1	2.2	1	2.2	4	4.4
Gerres cf. *plumieri*	2.2			1	2.2			1	2.2
Gerres sp.	3.5	120	420	113	395.5	25	87.5	208	903
cf. *Gerres* sp.	3.5			17	59.5	7	24.5	24	84
Diapterus auratus	2.4	7	16.8	5	12			12	28.8
Diapterus sp.	2.4	3	4.8	1	2.4			4	7.2
Haemulon cf. *plumieri*	3.8	2	7.6					2	7.6
Haemulon cf. *sciurus*	3.5			1	3.5			1	3.5
Haemulon flavolineatum	3.5			2	7			2	7
Haemulon cf. *flavolineatum*	3.5			3	10.5			3	10.5
Haemulon aurolineatum	4.4			2	8.8	1	4.4	3	13.2
Haemulon cf. *aurolineatum*	4.4	2	8.8					2	8.8
Haemulon carbonarium	3.7	2	7.4	3	11.1			5	18.5
Haemulon sp.	3.6	166	597.6	134	482.4	43	154.8	343	1234.8
cf. *Haemulon* sp.	3.6			5	18			5	18
Conodon nobilis	3.6			3	10.8			3	10.8
Anisotremus cf. *virginanus*	3.6			1	3.6			1	3.6
Anisotremus surinamensis	3.6			7	25.2			7	25.2
Anisotremus cf. *surinamensis*	3.6	2	7.2					2	7.2
Anisotremus sp.	3.6	14	50.4	3	10.8	2	7.2	19	68.4
cf. *Anisotremus* sp.				3	10.8			3	10.8
Rhonciscus crocro	4					1	4	1	4
Calamus calamus	3.5	5	17.5					5	17.5
Calamus sp.	3.5	6	21	15	52.5	6	21	27	94.5
cf. *Calamus* sp.	3.5	3	10.3	8	28	3	10.5	14	48.8
Archosargus rhomboidalis	2.9	1	2.9	3	8.7	3	8.7	7	20.3
Archosargus cf. *rhomboidalis*	2.9			9	26.1			9	26.1
cf. *Archosargus* sp.	2.9			4	11.6			4	11.6
Sciaenops sp.	3.7			3	11.1			3	11.1
cf. *Sciaenops* sp.	3.7	4	14.8	3	11.1			7	25.9

Supplemental Table. 4 Trophic level values for all the identified fish species. Trophic level values from the fish base database.

cf. E*quetus* sp.	3.5					1	3.5	1	3.5
Umbrina sp.	3.1	1	3.1					1	3.1
cf. *Umbrina* sp.	3.1					1	3.1	1	3.1
Micropogonias furnieri	3.1	2	6.2	5	15.1			7	21.3
Micropogonias sp.	3.1	2	6.2					2	6.2
Bairdiella ronchus	3.5			1	3.5			1	3.5
Bairdiella cf. *ronchus*	3.5	1	3.5					1	3.5
Pareques cf. *acuminatus*	3.6			1	3.6			1	3.6
Bodianus rufus	3.7			1	3.7			1	3.7
Bodianus cf. *rufus*	3.7			1	3.7			1	3.7
Bodianus sp.	3.7	1	3.7			1	3.7	2	7.4
cf. *Bodianus* sp.	3.7			1	3.7			1	3.7
Halichoeres sp.	3.8	1	3.8					1	3.8
Scarus sp.	2	6	12			1	2	7	14
cf. *Scarus* sp.	2			9	18			9	18
Saprisoma cf. *chrysopterum*	2	2	4	1	2			3	6
Sparisoma sp.	2	9	18	6	12	7	14	22	44
cf. *Sparisoma* sp.	2			1	2			1	2
Epinephelus guttatus	3.8			1	3.8	2	7.6	3	11.4
Epinephelus cf. *guttatus*	3.8			2	7.6	1	3.8	3	11.4
Epinephelus sp.	3.8	12	45.6	19	72.2	9	34.2	40	152
cf. *Epinephelus* sp.	3.8	14	53.2	13	49.4	4	15.2	31	117.8
Mycteroperca sp.	4.3	1	4.3	1	4.3			2	8.6
cf. *Mycteroperca* sp.	4.3			1	4.3			1	4.3
Cephalopholis cf. *fulva*	4.1			1	4.1			1	4.1
Cephalopolis sp.	4.3	6	25.8	5	21.5	3	12.9	14	60.2
cf. *Cephalopolis* sp.	4.3	2	8.6	5	21.5	1	4.3	8	34.4

Supplemental Table. 5 Radiocarbon Dating extra data.

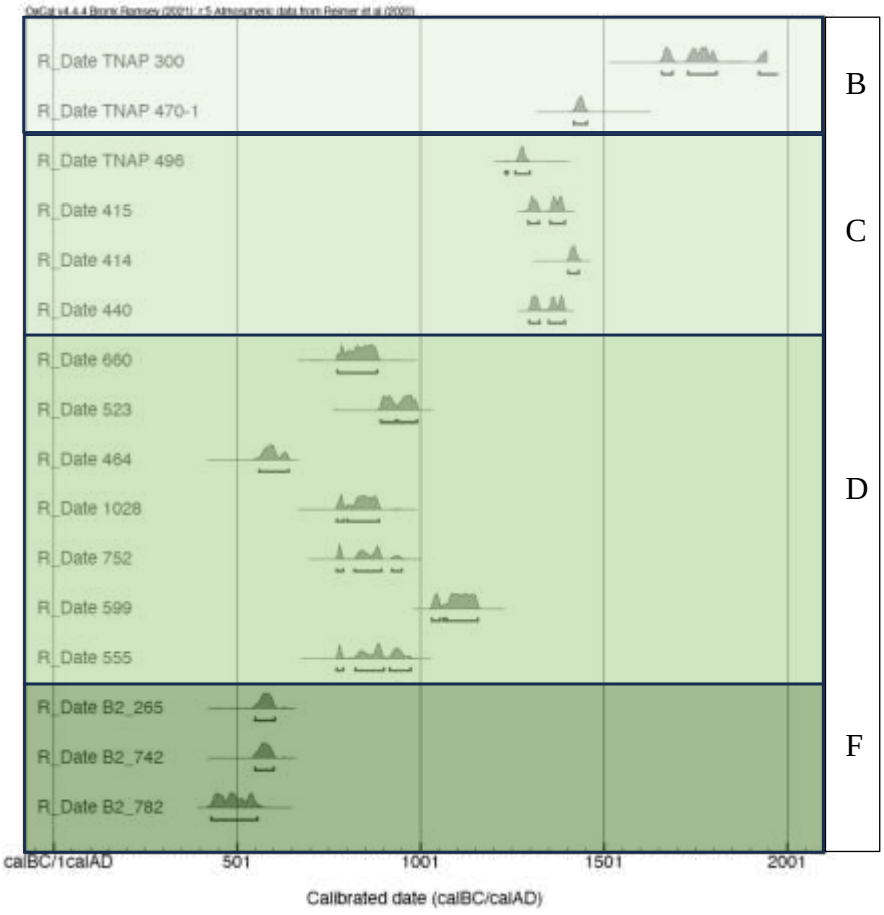
UCIAMS #	Sample name	Level	Strata	Other ID	$d^{13}C$ (‰)	±	fraction Modern	±	$D^{14}C$ (‰)	±	14C age (BP)	±
248908	TNAP19 Bag 415 2019, 43.5 cmbd char	6	C				0.9236	0.0017	-76.4	1.7	640	15
248909	TNAP19 Bag 440 2019, 52 cmbd char	8	C				0.9240	0.0016	-76.0	1.6	635	15
248910	TNAP19 Bag 660 2019, 65 cmbd char	10	C				0.8613	0.0015	-138.7	1.5	1200	15
248911	TNAP19 Bag 752 2019, 82 cmbd char	14	D				0.8646	0.0015	-135.4	1.5	1170	15
261607	T P19 Bag265 Bl.2 30-35cm char.	4	B	30	-25.5	0.1	0.8296	0.0015	-170.4	1.5	1500	15
261600	T P19 Bag414 Bl.1 40-45cm char.	6	C	40	-26.0	0.1	0.9372	0.0016	-62.8	1.6	520	15
261608	T P19 Bag742 Bl.2 50-60cm char.	7	D	50	-26.5	0.1	0.8291	0.0015	-170.9	1.5	1505	15
261609	T P19 Bag782 Bl.2 60-70cm char.	8	D	60	-26.2	0.1	0.8224	0.0018	-177.6	1.8	1570	20
261604	T P19 Bag523 Bl.1 65-70cm char.	11	D	65	-25.1	0.1	0.8708	0.0015	-129.2	1.5	1110	15
261601	T P19 Bag464 Bl.1 75-80cm char.	13	D	75	-25.0	0.1	0.8316	0.0019	-168.4	1.9	1480	20
261605	T P19 Bag524 Bl.1 75-80cm char.	13	D	75	-24.6	0.1	0.8621	0.0015	-137.9	1.5	1190	15
261606	T P19 Bag599 Bl.1 80-85cm char.	14	D	80	-24.8	0.1	0.8885	0.0015	-111.5	1.5	950	15
261602	T P19 Bag555 Bl.1 85-90cm char.	15	D	85	-24.6	0.1	0.8656	0.0017	-134.4	1.7	1160	20
261603	T P19 Bag1343 Bl.1 110-115cm char.	19	F	110	-24.4	0.1	0.5885	0.0011	-411.5	1.1	4260	15

Continuation left side of the Supplemental Table.5 Radiocarbon Dating extra data.

Calibrated Age Range (calBP)	Calibrated Age Midpoint (calBP)	Probability									
655	557	95.4									
654	556	95.4									
1176	1067	95.4									
1179	1001	95.4									
1400	1347	95.4									
546	517	95.4									
1401	1350	95.4				1034	977	32.1	1178	1161	12.4
1520	1394	95.4									
1058	959	95.4	1011	959	53.3	1058	1017	42.1			
1390	1310	95.4				1177	1158	16.1			
1177	1062	95.4	1150	1062	79.4	917	896	16.1	886	883	1.1
917	793	95.4	878	793	78.2						
1178	977	95.4	1127	1050	50.9						
4855	4829	95.4									

SUPPLEMENTAL FIGURES

Supplemental figure. 1 Radiocarbon for all stratums of Tierras Nuevas 2019.



CONCLUSION

As climate change continues to escalate in manners not previously observed by society, communities affected by it are desperately seeking answers and hope for the future. Some of the questions the communities have had led this research: How will it look, how will the ecosystem resist, and how can we adapt to those changes? This dissertation uses the anthroposystem/socio-ecosystem framework to understand how the conditions affecting us in the present have affected Indigenous societies and marine ecosystems in the Caribbean. Even though contemporary and past societies may not be directly comparable, the deep historical and time perspectives used in archaeology can provide valuable data for present and future scenarios.

Looking into the abiotic, biotic, and cultural variables made it possible to examine how past societies and the marine ecosystem were affected by climate change. Chapter one examines the abiotic characteristics during 800-1300 CE, focusing on conditions around 900-1000 CE when cultural changes were registered around the Caribbean. One of the major changes seen in the cultural component is the diet, which is attributed to the overexploitation of marine resources. The data gathered in the first paper indicates a probability that the climate changes that occurred during 800-1000 CE could have affected the marine ecosystem by the presence of elevated sea surface temperatures and increased storminess. During this time, the Medieval Climate Anomaly was occurring, generating changes that were felt strongly in the northern hemisphere; however, studies on how it could affect the Caribbean region are not abundant and did not present robust data to go deeper in time.

Using the coral fragments present in two archaeological sites in Puerto Rico, Tibes (Ponce) and Tierras Nuevas (Manatí), it was possible to do a paleoecological reconstruction of their coastal ecosystems, as seen in chapter two. The paleoecological reconstruction allowed for

identifying coral reef systems on the northern and southern coasts and detecting centennial (centenarian) corals. Both Tierras Nuevas and Tibes presented a significantly similar pattern of chronology for the coral fragments present on the sites. Looking more closely at the coral and climate data for the 800-1150 CE timeframe, the coral decline or absence on both sites occurred during the climate conditions associated with the Medieval Climate Anomaly, and the flood evidence on Tibes suggests the landfall of intense hurricanes over the region as register in sediments cores around Puerto Rico. Paleoclimate models were built to address the conditions during this time and were able to establish periods of elevated sea surface temperatures associated with the MCA, indicating the probabilities of coral bleaching occurring during this time for the north and south coasts of Puerto Rico. These changes and conditions could decrease the presence of coral fragments on both sites.

Chapter 3 concentrates on the ichthyofaunal assemblage of Tierras Nuevas and Angostura in the Manatuabón valley. The ichthyofauna analysis of both sites presented a unique opportunity to study changes in the landscape and climate and if the utilization of the resources available in the regions during different occupations resulted in resource overexploitation. Both sites presented some similarities in the faunal remains assemblages; however, the ecosystem used for fishing presents variation between the sites related to the site's location in which the selections of nearby resources are noted. Landscape changes and the rising sea level do not seem to have affected the selection of the gathering areas. The size estimation analysis performed on the Icthyo fuanal assemblage of Tierras Nuevas indicates a regional pattern or fishing tradition and specific fishing tools, such as line, hook, gill net, and possible tramps. These results indicate that the fish were mostly gathered in the brackish waters and coral reef ecosystems near the site, and there is no evidence of overexploitation during the occupation of Tierras Nuevas. However,

the *Centropomus undecimalis* have been constantly caught by the pre-Columbina people habituating Angosturas and Tierras Nuevas. It was not possible to assess the fish size of the Angostura sample since it was not measured previously, and a revisit of the sample is required and suggested at least for the *Centropomus undecimalis* to see the size seen on Tierras Nuevas sample due to overexploitation of the specie or human and tool selection. On the site of Tierras Nuevas, dates ~950 to 1300 CE are not available; it is important to mention that the stratigraphy does not support the idea of possible abandonment of the site. The field season of 2023 would provide new radiocarbon dating to address the missing dates, allowing a better interpretation of the material assemblages and a more in-depth analysis with the paleoclimate models.

The results of this dissertation support community-based projects in which I participate as a volunteer and field leader, such as Vegabajeños Impulsando un Ambiente y Desarrollo Sustentable and Descendiente Unidos por una Naturaleza y Ambiente Sostenible. These projects work on restoring and preserving marine ecosystems and the cultural heritage along Puerto Rico's coastlines. A fourth global coral bleaching event currently affects the Caribbean region, and understanding past climate change can help to preserve current ecosystems. As part of the results of the dissertation, identifying the coral systems that were previously affected by coral bleaching and served as gathering areas for pre-Columbian societies that are still alive allowed us to locate resilient genetic variations of corals to restore the coral reef around the island. El Eco is one of the Sentinel coral reefs identified in this research, and it is one of the coral reefs whose genetic variation could have been exposed to the coral bleaching events identified during the Medieval Climate Anomaly.

Future isotopic and genetic analysis of the otoliths and coral fragments can provide valuable information for restoration projects and to better understand past human dynamics with

the marine ecosystems. The combination of otolith isotopes and coral DNA will provide paleoclimate data at a local and regional level, and the coral DNA can help identify other species not selected by humans and previously present in the region. Coral DNA analysis has been proven to be effective in the identification of species even if the coral has been severely modified by humans (as jewelry or tool) therefore, coral DNA present in the archaeological context with the current coral reef can help in the process of identifying the genetic variations of corals that can serve as a basis for the propagation of those specimens for the restoration programs in Puerto Rico and around the Caribbean.

Interdisciplinary research and collaboration, as the one performed for this dissertation papers, which combines archaeology (past societies), paleoclimate and development of paleoclimate models (abiotic), and ecology (biotic, past, and current), are necessary to ensure the sustainability and food resources of the coastal communities in Puerto Rico. Currently, conversation and work with the Department of Natural Resources from Puerto Rico, Sociedad Ambiente Marino, and VIDAS are in the process of performing genetic analysis of El Eco corals for their propagation of coral fragmentation to other parts of the island. The information gathered form this and future research provides hopes and ways to improve the conservation efforts many communities around the island are leading.

The study of the faunal assemblage of the archaeological sites allowed a connection between present coastal communities and their/our ancestors. Looking at how pre-Columbian societies used the ecosystems and how they were affected by past climate change allows us to start looking at new solutions and improvement of restoration efforts and promoting the protection of the areas.