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A Deep-Time Socioecosystem Framework to Understand Social Vulnerability on a Tropical Island

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ABSTRACT

Archaeological research has the potential to contribute to our understanding of social vulnerability to environmental change by providing examples of change in the deep and recent past. Here we argue that human activity and historical processes deeply transform tropical environments through time, and that these changes accumulate on the landscape affecting social vulnerability. These changes, however, are not always evident due to rapid vegetation growth obscuring past human impact. Our research investigates the northernmost 25 km of the Manatí Hydrological Basin in Puerto Rico, focusing on evidence of human activity and environmental characteristics including topography, sediments and vegetation cover. The data collected, which articulates archaeological and ethnographic records, covers the span of pre-Columbian occupation of the region, through the colonial periods, and into the twentieth century. Results show that human activity through time has deeply altered the forests. The accumulation of long-term histories of biotic, abiotic and cultural dynamics affects social sensitivity and exposure. Human ingenuity can widen resilience thresholds, making long-term practices particularly important components of adaptive strategies. Deep-time socioecological perspectives can contribute to current vulnerability assessments by enhancing local and historical records that can feed predictive models and inform decision-making in the present.

KEYWORDS

Social vulnerability; socioecosystem dynamics; environmental change; deep-time perspective; environmental archaeology; Puerto Rico

Introduction

The global environmental crises faced today have inspired different communities of action to invest in conservation efforts to restore and improve the environmental characteristics of ecosystems, particularly in ecologically sensitive areas such as tropical islands (Lowenthal 2013; van Noordwijk et al. 2014; Epting 2015; Peters, Hamilton, and Eames 2015). However, many of these efforts seldom consider the deep-time socio-natural legacies of the areas targeted for restoration and conservation. In the Caribbean, the idyllic lushness of green mountains surrounded by light blue beaches and white sand tangle with a reality that straddles between the tourist experience of relaxation and the stressful reality of island life facing the challenges of pre- sent climatic and environmental change. Within this context, tropical island vulnerability is hard to perceive, particularly by non-locals. This paper evaluates the *longue durée* of a hydrological basin in Puerto Rico to contextualise its social and environmental histories and to study how millennia of human alterations of the environment influence social vulnerability.

Here we argue that human activity and historical pro- cesses deeply transform tropical environments through time, and that these changes accumulate on the landscape affecting social vulnerabilities (Nelson et al. 2016). In this context, we define social vulnerability as the degree to which a society or its members are susceptible to, or unable to cope with, external stresses placed on their livelihood or well-being, including adverse effects of climate change, climate variability and extremes (Agder and Kelly 1999; Melillo, Richmond, and Yohe 2014, 672). The complexity of socio-ecological interactions can be understood through Braudel's deep-time perspective, or *longue durée* (Braudel 1949; Butzer 1982; Redman and Kinzig 2003; Bailey 2008; Braudel and Wallerstein 2009), which extends beyond the often descriptive accounts of historical ecology. Combined with a multiscalar framework, this approach facilitates the understanding of the dynamics of human decision-making by providing a deep-time perspective for integrating short-term datasets.

Research Framework

Archaeological contexts constitute palimpsests of environmental and social material evidence representing processes that occur at multiple temporal and spatial scales (Bailey 2007). This entanglement of material remains makes it particularly complicated to understand socio environmental dynamics. Differences in scale affect not only the observations we make and the things we can focus on, but also influence our understanding of the events and processes in the past or the present (Bailey 2007, 2008; Holdaway and Wandsnider 2008). Therefore, it is imperative to approach research with clear scale-awareness, and to conduct conscious scale shifting to avoid overly simplified conclusions, and the identification of coincidence as causality.

The socioecosystem can be visualised as three-dimensional structure composed of multiple nested dynamic components of different spatial-temporal scales (Holling, Gunderson, and Ludwig 2002, 5; Allen et al. 2014). The interconnectedness of the nested scales influences the overall vulnerability

of the system. Two of the most significant interscalar connections are memory (or 'remember') and revolt (Redman and Kinzig 2003; Redman 2005; Allen et al. 2014). Through memory, stability in larger and slower scales influences smaller and faster scales to continue adopting known and accepted behaviours as solution to crises, or to maintain a behaviour in spite of crisis. Through revolt, chaos and reorganisation at smaller scales influence larger scales to change when crises occur at a time when larger scales are vulnerable. The multiscale functioning can either support overall stability and robustness despite crisis; or enhance its vulnerability to change if the individual scales are facing chaos or instability (Berkes and Ross 2016). This integration of processes at multiple scales provides the deep-time perspective (Rosen and Rivera-Collazo 2012; Allen et al. 2014; Gorddard et al. 2016; Müller et al. 2016).

Successful articulation of natural and social processes requires linking of compatible scales (time/space), and avoiding mixing of disparate processes (Allen et al. 2014). For example: climate change is a process that is observed at a spatial range of the entire planet, and at a temporal range of millennia. The patterns of human subsistence, on the other hand, are processes observed at a spatial range of social territories (home range) and at a temporal range of several years. In this context, subsistence is the average of diet observations, which occur at even smaller spatial and temporal scales. Therefore, the socioecosystem model would predict that the direct consideration of the effect of climate change over human subsistence is misleading because these two processes occur at disparate scales. Articulating climate change to human subsistence would require downscaling climate change to the meteorological effects affecting the locality of the home range (abiotic context) and the distribution of resources relevant for human subsistence (biotic context), in order to be able to understand how climate change could affect people's subsistence behaviour. This scale awareness permits the ordered and coherent evaluation of multiple sources of data.

Problem Placement and Methods

This article intends to evaluate tropical environmental and social vulnerabilities at the present using a deep-time perspective to understand socio-natural characteristics. In the context of this research, the TAC is used as inspiration for the proposed three-dimensional socioecosystem, and as a heuristic framework to organise data, and to structure the process of analysis of multiple sources of information. As case study, the research focused on the hydrological basin of the Manatí and Encantado Rivers, which has been inhabited for about 5000 years (Rivera-Collazo 2015). The research focuses on landscape use patterns through time, their effects over tropical ecosystem distribution, and the social variables of landscape use, specifically subsistence acquisition and settlement patterns.

The research studied the northernmost 25 km of the Manatí River Hydrological Basin, from the town of Ciales on the south to Barceloneta and Manatí to the north (Figure 1). The study area sampled an ecologically diverse section of Puerto Rico's northern coast which includes the shoreline (Line A), the low-lying coastal plain (Line B), the karstic hills (Line C), and the foothills of the volcanic central mountain range (Line D). To sample the diversity of the study area, the project selected study lines at the seashore, at the beginning of the karst area, in the middle of the karst area and at the foothills of the volcanic region (Figure 1).

Study lines were divided in five survey locations: two at 2 km east and west of the river, two at 1 km east and west of the river, and one adjacent to the river, alternating the east and the west bank. Line D was a modification of the plan and, while it retains the survey requisites regarding distance to river, only the western side of the basin was inspected. Each survey location covered an area of 200 m × 220 m. Each search area was subdivided in five transects at 40 m intervals with observation points every 40 m. Base lines were arranged in a north to south alignment, and all transects ran from east to west. To enhance coverage of observation, transects 2 and 4 in every location were offset 20 m from the baseline to form a hexagonal grid.

All locations were systematically inspected to register archaeological and ecological data. The area of all observation points within the transects was standardised to 1 m^2 where sediment texture, colour, type and density of vegetation, inclination, and type and abundance of artefacts (if any) were recorded in standardised forms. Additional observations were also made in between transects and between observation points with GPS. At each site, we also documented land use (urban, forest, agriculture) and forest age (young or mature) using as indicator the perceived thickness and proximity of trees. The presence and distribution of domestic fruit-bearing species were also documented as evidence of anthropogenic manipulation of forests.

In cases where the observation location coincided with an urban or developed area, field-method shifted to ethnographic interviews and observation/documentation of historic remains in the area. Ethnography consisted of open interviews with guided questions focusing on individuals older than 60 years of age who have lived in the study location for a minimum of 10 years. Between three to eight people were interviewed at each location, except for Location 16 where only one person was interviewed. The ethnographic methodology received approval of an ethics research board, and all interviewers were certified on research ethics when working with human subjects. To articulate the interviews with the archaeological survey, individual interview questions focused on three main themes: personal history, environmental history and local history; focusing on subsistence, settlement, vegetation, topography and perception of climate.

Survey and ethnography were complemented with archaeological data from all the project reports at the Institute of Puerto Rican Culture and the State Historic Preservation Office within the study

area (1970s– 2014). The chronology of archaeological data in this article is based on the dates reported on the archival reports, or the typology of the materials identified on the field (see Supplement 1 and Supplement 2).

The research strategy of surface survey over a broad horizontal region, limits the resolution to which observations can be made as we move back in time, given that higher detail of the past requires more detailed analysis of the research variables from archaeological contexts. However, this approach does allow for a high-quality understanding of the social processes within the basin through time and their characteristics today. Higher complexity should become evident with more in-depth investigation and sub-surface testing.

Results and Discussion

Survey teams could not secure access to Locations 8, 9, 10, 11 and 14. Alternative Locations were identified for 8 and 11, and additional Line D was designed to replace Locations 9, 10 and 14. The summary of survey results for each location is included in Supplement 1. The results are organised in Table 2 and Figure 2.

The survey strategy allowed for the acquisition of large amounts of data from multiple proxies. Data were divided in three scales: (1) a small scale of high resolution information within the last several decades at each location (communities, generations); (2) a medium scale of processes occurring over hundreds of years on the hydrological basin (traditions), and (3) a large scale of processes occurring over thousands of years throughout the region (cultures) (Table 1).

The Small Scale (Communities, Generations)

The results discussed at this scale are strongly based on the ethnographic accounts and oral histories (Supplement 1: Locations 5, 7, 12 and 16), expanded with the field observations at all Locations. Data at the small scale of decades were only visible for the twentieth Century, or the life experiences of the interviewees (aged between 65 and ca. 90 yrs on 2014). The cultural variables considered are house construction and subsistence acquisition strategies. The biotic variables considered are changes in the distribution of plants and animals, forest recovery, and alteration of the immediate landscape within each location. The abiotic variables considered are land-forms and their anthropogenic modifications.

Physical evidence of the impact of human activity was recorded in all Locations (Table 2). The types of impact observed included scattered household and industrial refuse or debris accumulation, mining, road building, off-road traffic, housing development, and land-form modification such as terracing for houses and agriculture, or massive land-movement. In terms of

vegetation, seven locations were totally or partially covered in forest, while 10 others were deforested. All forested locations had young forest cover and most also had domestic fruit-bearing trees or decorative plants. The locations without tree cover had signs of recovering plant colonisation sequence, such as grasses and thorny weeds, or evidence of erosion (Supplement 1: e.g. Locations 8 and 18).

The study identified two intertwined groups, which are not easy to label or fully separate. The oral accounts differentiate between a 'them' and an 'us': the 'them' being used in reference to specific families (such as the Calaf in Location 7) or individuals (e.g. Doña Juanita Ortolaza in Location 12). The narratives about 'them' point them out as having strong economic power, large land-tenure, and control of the industrial production of cash-crops – such as sugar, coffee, tobacco or cattle herding – as well as the job market associated to it. These narratives stemming from the ethnography resemble the class divisions of an elite group, reason for which we adopt this term in the rest of the description, but emphasise that the word was not used by the informants. No specific term was used to distinguish the elite aside of maybe the use of the determinant article *los*, often followed by a specific surname as a group identifier (i.e. '*los Calaf*'), and a sense of power relationship.

In some cases, a distinction was made regarding the European ascendency of the elite or their outsider roots linked to the metropolitan areas of San Juan or Bayamón. However, this characteristic alone is not enough to differentiate them. One individual did mention having ascendants from Spain or the Canary Islands several generations before him, but somewhere in his recent past a family member lost everything before his descendants settled in the urban areas. The informant's interaction with other people during interviews was not consistent with the 'elite' identifier, supporting the fact that having European ascendency is not enough to distinguish between classes. Most of the interviewees reported having local roots, within the study area (from the townships of Ciales, Utuado, Morovis, Manati, Florida, Orocovis).

The monetary income of the non-elite was dependent on the work opportunities stemming from the market economy, which was controlled by the elite. Up until recently, traditional non-elite house construction methods were characterised by the use of wood or other perishable materials. In contrast, construction methods associated with the elite are characterised by the use of brick or cement, or cement / brick and wood. Material evidence of elite presence (e.g. concrete or brick houses, haciendas, bridges), and the ethnographic account of their influence were recorded in many Locations (see Supplement 1).

Two different subsistence strategies were identified: self-sufficiency and market economy. Self-sufficient economies base the subsistence on self-produced or locally sourced products. Activities within this economy included agriculture, livestock kept within the community – either in pens or

free roaming – hunting, fishing and gathering. The crops and animals are presented in Table 3. Hunting activities occurred in forests and wetlands, and fishing activities, in the river and the sea. Gathering activities targeted fruit-bearing trees within and around the communities, many of which can still be observed overgrown in recovering forests (see Table 3). Cultivation employed open-air planting with ploughing, slash-and-burn or terracing methods. This last one was observed only on the most inclined topographies, and entailed building stone walls to create flatter areas and maintain the soil over eroded, rocky limestone hills. Slash-and-burn agriculture was only recorded ethnographically by an informant who reported that her father practiced agriculture 'the way the Indians used to do it': cutting down and burning the forest, and using the green wood to make charcoal. The informant called this type of agriculture *chimba* (Supplement 1, Location 12).

The second subsistence resource acquisition strategy identified was the market economy. It entailed acquiring foodstuffs – brought from the ports in San Juan, and from different areas on the countryside – from local shops within the communities. This economy was combined with household gardens, where some crops were produced to complement market availability. Interestingly, community support networks were an important part of both the self-sufficient and the market economies. Barter was recorded both in rural and in urban areas, where the individuals shared fruit and meat in the untold expectation that their generosity would be reciprocated. This was particularly important in the self-sufficient economies, where it extended also to supplying non-subsistence needs, such as midwives and healers (see Supplement 1, Location 12). Ethnography also permitted the identification of an additional and very important element of the community support network that overlapped the barter and the market economy: the *fia'o* system. This tradition allowed people to receive products at a shop under the guarantee that it was going to be.

The Medium Scale (Traditions)

The medium scale in the cultural panarchy encompasses the spatial constraints of each Line paid the following week. Getting *fia'o* was part of the regular subsistence acquisition practices, at least of the non-elite groups, and was also used as a buffer against the effects of economic instability or job insecurity.

In addition to subsistence agriculture, the non-elite also included tobacco or coffee within their crops. These products were not for household consumption but to sell to the elites, articulating the self-sufficient and the market economies through the coin-flow and the subsistence and settlement patterns through last several centuries, thus extending into the historical archaeology record. There is no concrete analysis of subsistence patterns during the historic period within reports consulted in the archival analysis. Therefore, analysis of change in subsistence patterns is based on the oral histories recovered through ethnography and the material evidence identified on the surveys. In the

biotic and abiotic contexts, the medium scale refers to shifts in forest cover and erosional processes that could have altered the landscape characteristics within the hydrological basin.

Subsistence agriculture for individual households transformed modern ecosystems by altering the diversity of plant and animals on recovering forests. Terrace construction, for which deforestation and wall building was required, transformed the karstic hills and forests. Slash-and-burn agriculture opened up forested areas. Open-air agriculture requires deforested areas, so either forests were cut down to cultivate or agriculture occurred on already impacted landscapes. The informant that reported *chimba* mentioned that, once her family migrated to the location where she was interviewed (from somewhere along Line D to Location 12) her father changed his cultivation strategies because there was no forest to cut.

Parallel to subsistence-related agriculture, the elite engaged on large-scale cash-crop production of sugar, tobacco, coffee and cattle. These activities, while did have effects on the daily lives of the non-elite, are linked to processes of market demand and supply that extend beyond the study Lines, the study area and the region. Historical accounts place the beginning of intense deforestation on the island at the end of the 18th and beginning of the nineteenth centuries (Picó 2015, 181). Logging occurred to clear fertile soils for tobacco and sugarcane cultivation, to fuel plantations, and to exploit hardwoods. As cash-crop, coffee requires a different planting strategy, requiring more shade than sugar and tobacco. Therefore, places where coffee was planted are not as severely impacted as those dedicated to cattle herding, tobacco and sugar (see Supplement 1, Location 18). Table 2 demonstrates that the areas where the study found evidence for sugar, tobacco and herds of cattle were produced in the past, the landscape is still deforested today, while areas where coffee was grown present forest recovery. Widespread deforestation of the mountainside due to the agricultural practices caused severe erosion which could have either removed discrete deposits of individual households, or buried early deposits (Grau et al. 2003; Rivera-Collazo 2015).

Regarding settlement patterns, two types of communities were identified at the studied locations: rural, and urban or semi-urban. Within urban and semi-urban communities, the settlement pattern presented a conglomerate of buildings following a predictable pattern: the elite residential, administrative, market and industrial structures, gathered around the central plaza and the ritual structure (church). Non-elite residential structures surrounded the elite core. In rural areas, elite and non-elite houses are dispersed, although where non-elite houses group around elite structures, a semi-urban community ensues. In rural areas, the landscape was divided in land-plots (*cerca'os*) demarcated with trees or other plants (see Supplement 1, Location 17 for ethnography and Locations 1, 2 and 4 for archaeological evidence). Elite influence over settlement organisation, that is, the concentration of habitation around a central urban place, is more evident in the northern (coastal) lines (see Table 2). This pattern of organisation is similar to European traditions and

coincides with the historical observation of preferred European settlement on the coastal plains. The rural pattern of dispersed settlement is more common on the more southern lines, higher up in the mountains. Similarly, self-sufficient subsistence was registered on Lines C and D, while market economy was registered on Lines A, B and C. This non-elite pattern of settlement and subsistence has to be understood in a deeper temporal context.

The market and self-sufficient economies described above, and the interactions between these, were observed in the life history of the interviewees, and were also visible in the archaeological remains of abandoned places. However, practices today show a discontinuity with the past traditions. An important factor that seems to be linked to the start of these changes is migration. The ethnography showed migration to be an important part of the characteristics of the interviewed communities. In all cases, people had moved from the rural countryside (southern lines) to urban or semi-urban areas (northern lines) at the beginning of the twentieth Century. The archaeological survey showed widespread evidence of abandonment of rural communities, particularly on the mountains (see Table 2).

The recorded oral histories documented that the rural-to-urban migrants worked for a generation at their new urban or semi-urban communities. Their children (second generation) migrated either to San Juan, or to the United States (often linked to military recruitment). During their time away, the children sent money back, and the parents changed their houses from wood/organic materials to cement or cement and wood (see Supplement 1, Location 7), demonstrating an attempt to change their material manifestation of class and economic power identification. The second generation migrants later returned to the place where they grew up, but in many cases, their children (third generation) have moved on to other locations, often setting permanent residence in the USA. This destabilisation of the non-elite communities seems to be tied to two possible causes: the change in the colonial status of the Island, from Spanish to USA colonial powers; and the collapse of sugarcane, tobacco and coffee industries after the 1950s and 1960s. This destabilisation is coupled to the change in the structure of the market economy, from local markets to non-local shopping malls. This change has also destabilised the community support networks, disintegrating the *fia'o* support system and significantly weakening the barter system. The barter tradition, however, still remains in some older members of the communities, who share the produce of their gardens, but cannot work the land to enhance production.

The Large Scale (Cultures)

In the cultural panarchy, the large scale encompasses several archaeologically identified cultural periods: Archaic, Saladoid, Early Ostionoid, Late Ostionoid, Spanish colonial and American (USA) colonial. These are traditionally grouped in two large Ages, the Pre-Columbian (before 1492) and the Historic (after 1492). Within the biotic and abiotic contexts the large scale refers to the land-

form characteristics of the island and the tropical biome they support. Today the biotic component is represented by mixed moist and very moist forests on limestone, sandy and alluvial surfaces. Modern precipitation parameters support very moist forests only on the uppermost areas of the karst, adjacent to the Central Cordillera (Lugo 2005, 455–475). Other ecosystems within the study area include offshore coral reefs and rocky shores to the north of the eolianite ridges. At this scale, spatial constraints are at the level of the entire study area, within the context of the region.

At a large scale, settlement patterns show a continuation in spite of the crisis that was expected due to the European conquest that started in Puerto Rico after the first decades of the 1500s (not 1492). The study area features in the earliest mentions of the Conquest, as Juan Ponce de Leon and Juan Gonzalez established a short-lived camp at the river mouth (possibly near Location 3) in 1508, and later mined the river for gold, interacting with a native settlement by the name of Yamanatuabon (Baeza 1961). The archaeological remains of this indigenous settlement could be either the site of Tierras Nuevas (Location 3) (Dávila 1979, 11) or Bateyes (located further up the river, at the top of the karst range, south of Location 14). Permanent European settlement, however, did not occur until later in 1645 when the hermitage that gave birth to the town of Manatí (Location 7) was established. These hermitages or missions were often placed to serve and Christianise local dispersed communities of people by constructing new social and ideological orders through the appropriation of the landscape and the past (Schwaller and 1996; Parcero Oubiña, Criado Boado, and Santos Estévez 1998). This suggests the presence of at least dispersed communities in the area during the seventeenth century, which have not yet been considered archaeologically or historically.

Based on the available information (see Supplement 2 and Figure 1), and taking into account that the chronologies of the period require significant improvement, the distribution of indigenous (pre-Columbian) sites suggests a single trend that broadly continued from the Archaic to the present. During the Archaic Age, there is a single large settlement on the coastal plain (Angostura) and a cave site inland at the top of the karst range, overseeing the river and the river valley (Archillas cave). During the Ceramic Age in general – but mainly reflecting the patterns of the Ostionoid period given that little information is available on the Saladoid period – site distribution suggests the presence of two central sites, one on the coast and one inland at the top of the karst range, both immediately next to the river. These two large sites which feature multiple ball courts and mounds, were locations where smaller, dispersed communities and households could gather, as proposed by Torres (2008) for the Southern landscape around Tibes.

During the Ceramic Age, the archaeological record shows the presence of large-scale markings of the landscape, including highly visible petroglyphs at the foreshore and less accessible markings in caves and rock shelters (Supplement 2). Caves are usually interpreted as sacred areas, but the

meaning of the pre-Columbian cavescapes has not been investigated in sufficient detail (Samson et al. 2013).

During the Historic period in general there are also two large sites (towns), one at the coastal plain and one at the top of the karst range. At the coast, the town of Manatí is located 7 km south of Tierras Nuevas (Location 3), and basically at the same level of Angostura, but on the eastern bank of the River. It is possible that the location was selected away from the shoreline to protect the community from the pirate activity common between the seventeenth and eighteenth centuries and still part of the local oral memory (Supplement 1, Location 7). The town of Ciales, founded in 1820, is located at the top of the karstic range, less than 1 km south of the pre-Columbian site of Bateyes. Just as the pattern observed during the pre-Columbian period, both historic towns are surrounded by multiple habitation sites scattered around the landscape. Some small-scale habitation could also have occurred in caves, as suggested by the finding of archaeological refuse within a rockshelter on Location 1 (see Supplement 1), but it seems that the most common use of caves during the historic period was for the mining of guano (see Supplement 2).

If we accept the cavescapes to have ritual meaning due to the presence of petroglyphs; discontinuity and break in tradition might be observable in ritual practices in the archaeological record. During the historic period, ritual spaces were moved from the caves to the centre of town as represented by the location of Catholic churches. However, it could also be argued that ritual spaces within 'town' were also present in pre-Columbian sites as represented by petroglyphs around the batey plazas, as documented in Location 3. It could also be argued that caves have retained a ritual value in historic periods, as evidenced in Maria de la Cruz cave (Oliver and Rivera-Collazo 2015) where the cave space continues to have ritual significance for ceremonies of different traditions in the present. This would have to be further examined with future research. Regarding landscape markings, such as petroglyphs, there have been no studies on markings on the landscape during historic period, although there are marks along roads to commemorate people who have died, and there is a stone-memorial with text next to the Mata de Plátano bridge (Location 13) marking the landscape and reminding of a historic event.

Cultural continuities with pre-Columbian practices are perceptible in the subsistence strategies of the non-elite. Even though no direct analysis of archaeological artefacts was conducted at the pre-Columbian sites for this study, the archaeological literature on indigenous subsistence practices in Puerto Rico indicates a long-standing tradition that begins in the Archaic period with earlier roots in Caribbean mainland practices (Newsom and Wing 2004; Pagán Jiménez et al. 2005; Pagán-Jiménez et al. 2015; Rivera-Collazo 2015). Aside of the new crops and livestock introduced to the island during the Historic period, the basis of the non-elite subsistence agriculture is very similar to the pre-Columbian basic crop suite (Table 3). The archaeological evidence suggests that pre-Columbian subsistence strategies also incorporated arboriculture (including fruit gathering and

management of trees and plants) as well as hunting and fishing (Newsom and Wing 2004), all of which were documented in the ethnography. Pre-Columbian house building materials and house morphology area also almost identical to those observed for the non-elite groups. These subsistence and settlement practices see a direct continuation into the non-elite traditions documented at the small scale (see Tables 2 and 3).

Articulating the Scales: the Deep-Time Perspective

The deep-time socioecosystem framework proposes the articulation of dynamic temporal and spatial scales by focusing on the inter-relations and interactions between scales, and in particular memory and revolt. Focusing on the case study, we identified two cultural practices: the elite and the non-elite. Among the non-elite, the data available suggest that the practices of obtaining subsistence resources (small scale) and the settlement patterns along the hydrological basin (medium scale) show a continuation of indigenous traditions that was uninterrupted by the expected chaos of the Conquest (large scale).

The relationship with the microlandscape, including house building (i.e. the building materials, and architecture styles), the maintenance of house gardens, the type of crops planted, the exploration of the forests for hunting and fishing, the use of local plants and the location and distribution of settlements (centralised or not) also presents broadly uninterrupted traditions. This interscalar continuation suggests that indigenous ('pre-Columbian') traditions within the study area at the macro scale might not have fully disappeared after European conquest, but continued being reproduced by ethnically diverse, socially indigenous groups. Ethnical diversity was not foreign to the indigenous groups of the fifteenth and sixteen centuries, as illustrated by the concept of 'tainoness' put forth by Rodríguez Ramos (Oliver 2009; Rodríguez Ramos 2010).

The abandonment of ballcourts and of the traditional pre-Columbian practice of large-scale iconographic landscape marking and the ritual use of caves suggest a disintegration of the religious and ritual traditions that are usually regulated by the elites of social groups. This suggests that the indigenous elites were particularly affected by the chaos and reorganisation after the Conquest. The traditional practice of building houses using wood or other plant materials did not continue in the 'post-Columbian' elites, who built their houses using stone (the Manatí hermitage), brick, or concrete (after the twentieth Century) strongly following European or United States practices. These elites also show a clear focus on market economies through the exploitation of gold (fifteenth Century), coffee, sugar, tobacco, and cattle; largely modifying the landscapes, in particular after the nineteenth Century. It remains to be seen to what extent other practices can be identified as different between these two groups.

The deep-time memory of subsistence and settlement in the non-elite groups awarded them flexibility to withstand many changes through time. In the present, this set of traditions are currently under deep transformation and instability given that both elite and non-elite groups show evidence of restructuration. As identified in the ethnography, these changes are rooted within the large-scale economic transformation towards widespread industrialisation of the 1950s and 1960s, triggering local and overseas migrations and eventually removing the market from within the communities to an external point – the shopping mall – which is disintegrating communities by eliminating the *fia'o*, barter and self-sufficient subsistence strategies. These changes are themselves contextualised within the macro scale (global) processes that directly impacted the Island at the end of the nineteenth Century with the Spanish-American War. This cultural instability altered the mesoscale of the elite, and caused change to settlement patterns and subsistence base of the non-elite at the microscale. These changes, identified in the deep-time analysis of society, can be expected to be transformative given that the traditional practices and knowledge that had provided social-stability for the non-elite groups – even through the deeply traumatic European Conquest – are rapidly disappearing and will most probably be lost within a generation.

The entire study area has been impacted by human activity through time, deeply altering the island since the earliest of pre-Columbian occupations, from the introduction of species (plant and animal), to the transformation of forests (including deforestation), and the intentional or unintentional alteration of landscapes (e.g. pre-Columbian ballcourts, road construction, erosion after deforestation). Large-scale activities of the elite had and continue having a very significant impact on forest composition and distribution. In spite of the intensity of human activity, tropical forests show very high resilience. They recover and grow quickly, covering the evidence of human impact and masking the potential crises caused by reduced biodiversity, extirpation of native species and uncontrolled reproduction of non-native ones.

Conclusion

The goal of this study is to contextualise social and environmental histories and study local tropical environmental and social vulnerability. The *longue durée* framework and the socioecosystem model were applied to the case study to organise recent and deep-time, to identify landscape use-patterns, use of forest and river resources, and to evaluate long-term vulnerability. The application of this heuristic model allowed the identification of two co-existing traditions with different vulnerabilities. The differences between them reflect the memory of deep-time communities.

The forests we work to protect today are the product of many hundreds of years of human manipulation, the complexity of which had not been previously understood, and certainly need more attention. Intensive mechanical land modification, mining, and large-scale stripping of soils in the last few decades enhance biotic stress. This observation is particularly relevant because the

hydrological basin under study is the focus on intense conservation processes, particularly under the leadership of the Conservation Trust of Puerto Rico. This study contributes to a deeper understanding of the socio-ecodynamics shaping the areas that are today considered of high natural value.

In the context of the case study, social vulnerability is reduced through the continuation of long-term traditions based on local, regional and long-distance social support networks, and the maintenance of self-sufficient subsistence practices. For the non-elite, this knowledge is rooted in the deep-time memory of pre-Columbian traditions. Flexibility and adaptation in these characteristics allowed for continuation in spite of social or environmental changes through time. Traditional practices have been altered in the last 60 years as subsistence has moved towards a rigid market economy that has disintegrated traditional networks. These changes are increasing the social sensitivity to global change as anything that affects the supply to the rigid market will place subsistence in jeopardy. Therefore, social vulnerability at all scales can be expected to increase for both the elite and the non-elite groups, suggesting that, upon facing the projected climate and environmental changes in the present and near future, the studied communities will be highly vulnerable and prone to social crises.

An assessment of island vulnerability requires a consideration of the long-term history of the biotic, abiotic and social components of the islands. Human activity and historical processes deeply transform environments through time and those changes accumulate on the landscape affecting social sensitivity and exposure. Because of their ingenuity, humans have a very wide resilience threshold, making vulnerability a relative concept. Developing a deep-time socioecological perspective can contribute to current vulnerability assessments, enhancing local and historical records that can feed predictive models and inform decision-making towards successful adaptation.

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Geolocation Information

North: 18.4890, −66.5580; 18.4780, −66.5100. South:
18.2990; −66.5530; 18.3040, −66.4530.

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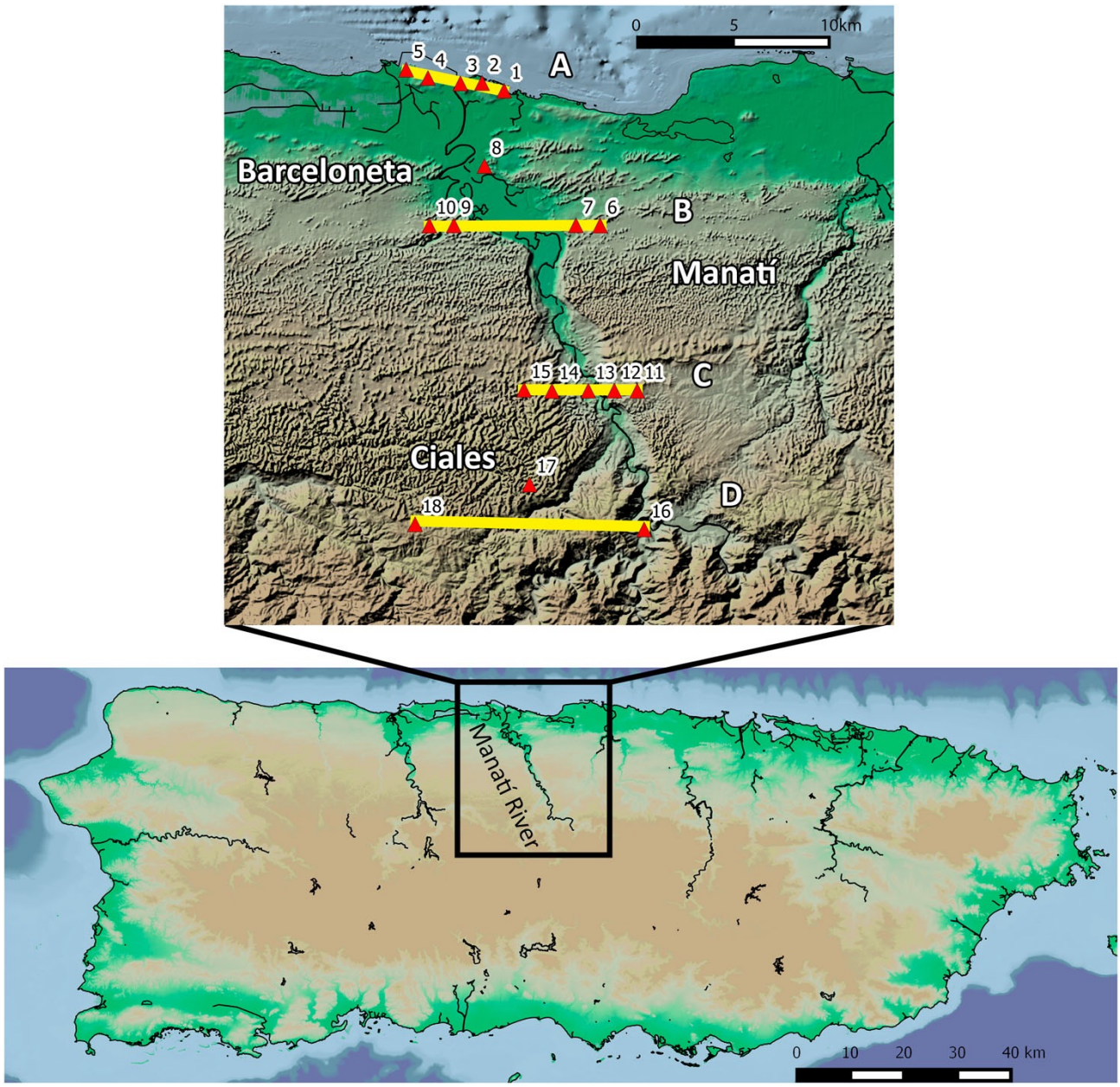
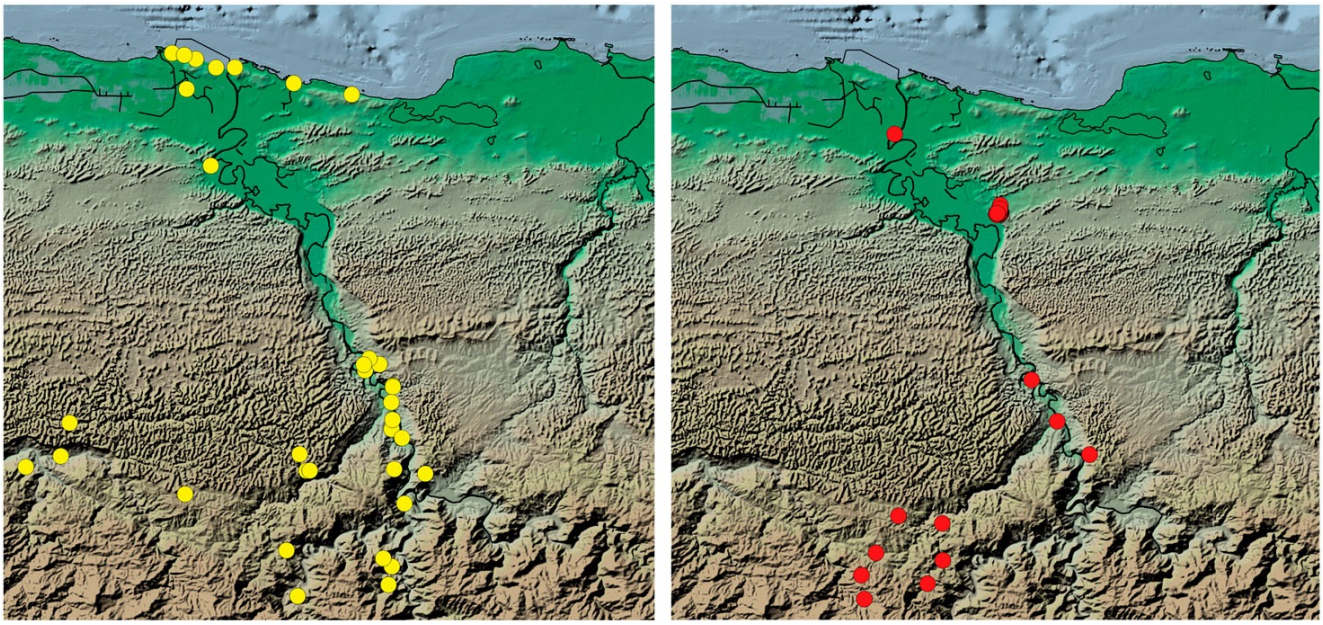


Figure 1. The hydrological basin of the Grande de Manatí and Encantado Rivers is located on the north-central part of Puerto Rico. The study area focused on the municipalities of Ciales on the south, to Manatí and Barceloneta on the north. The insert shows a close-up of the study area, marking lines A–D, and all study locations.



a. b.

Figure 2. Results of archival research. Image (a) shows the distribution of all reported pre-Columbian sites along the area. Very few of the sites have chronological information or reliable data. The image (b) shows the distribution of known Historic sites along the area. The official archaeological register is biased for pre-Columbian sites, and this not all known sites of historic importance are reflected in this map. Details are included in Supplement 2.

Scale Space/time	**Culture**	**Biotic**	**Abiotic**
Small Location/ communities, generations (<100 yrs)	House construction methods Subsistence resource acquisition strategies	Distribution of plants and animals Forest recovery	Land-form characteristics
Medium Line/traditions (centuries)	Settlement patterns Subsistence practices	Forest cover	Erosional processes
Large Basin/cultures (thousand years)	Culture change	Biodiversity and biotic change – tropical biome	Landscape change

Table 1. Scale-aware organisation of the data for this study.

Observations (ethnography and field survey)	Locations														
	Line A					Line B			Line C				Line D		
	1	2	3	4	5	6	7	8	11	12	13	15	16	17	18
Vegetation															
Deforestation (grasses, thorny weeds, exposed sediments)															
Young tree cover/forest recovery															
Reduction of fauna abundance/diversity															
Presence of domestic or decorative plants															
Anthropogenic influence over plant distribution															
Cattle herding															
Sugarcane cultivation in the past															
Tobacco cultivation in the past															
Coffee cultivation in the past															
Topography															
Refuse/debris on surface															
Anthropogenic modification of land surface															
Roads															
Off-road traffic															
Mining (limestone, river sand, river pebbles)															
Construction															
Settlement															
Rural (ethnography or archaeology)															
Dense habitation (small town or urban)															
Residential structure built of wood or organics															
Residential struct. built of cement/brick															
Residential struct. built of cement/brick + wood															
Administrative structure															
Industrial structure															
Water management structures															
Ritual structures															
Subsistence															
Fishing															
Hunting															
Gathering															
Free roaming livestock															
Open air agriculture															
Slash-and-burn agriculture															
Agricultural terraces															
Self-sufficient subsistence															
House gardens + market															
Local shop/market															
Barter															
Fia' o															
Migration															
Immigration from Spain															
Immigration from inland (south to north)															
Emigration towards San Juan or USA															
Abandonment															

Table 2. Summary of results according to the variables selected for this study.

Ethnography (Locations 7, 11 and 12)	Crops	Maize, manioc (cassava, *Manihot esculenta*), yams, sweet potato, yautía (*Xanthosoma*), squash, legumes (beans and peas), chilli pepper, plantain, banana, herbs. Tomato reported in urban setting
	Gathered fruit/ observed fruit trees	Guava, soursop (guanabana), avocado, breadfruit, mango, mavi, oranges, lemons, grapefruit, cupey and coconut
	Livestock	Cattle, rabbits, chickens, pigs, goats, pigeons, turkeys
Archaeology (pre- Columbian)	Crops	Maize, manioc (*Manihot esculenta*), yams (Dioscorea), sweet potato, yautía (*Xanthosoma*), squashes (Curcubitaceae), legumes (Fabaceae), chilli pepper, palms, and many different fruits and dicot products

Table 3. Cultivars targeted for subsistence in self-sustained economies.