Title

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Journal

The Journal of Island and Coastal Archaeology, 15(2)

ISSN

1556-1828

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Publication Date

2020-04-02

DOI

10.1080/15564894.2019.1570987

Peer reviewed

Severe Weather and the Reliability of Desk-Based Vulnerability Assessments. The Impact of Hurricane Maria to Puerto Rico's Coastal Archaeology

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Journal of Coastal and Island Archaeology. 2019. DOI: 10.1080/15564894.2019.1570987

Abstract

Within the context of climate change, sea level rise is threatening not only coastal communities globally, but also the archaeological record of their history, knowledge and culture. As a response, inter-institutional databases of heritage are increasingly been coupled with other widely-available cyberinfrastructure to assess the magnitude of the threat and the vulnerability of cultural heritage, in order to begin the design of actionable steps or mitigation of impact. This article focuses on the coastal archaeology of Puerto Rico to evaluate the damage caused by Hurricane Maria, and to assess the reliability of desk-based vulnerability assessments in the context of disasters. The study conducted a walkover survey of 11 km of coast on the north-central portion of Puerto Rico and documented context, visible impact, and level of threat from coastal erosion, among other factors. The study concludes that, for the case study, the desk-based assessment conducted in 2017 underestimated the vulnerability of coastal resources. While two sites were predicted to be vulnerable, the survey identified eight damaged sites. These results call for heightened attention to the actual process of sea level rise in the context of changing weather and changing water-level baselines, not just for cultural heritage, but also for coastal and marine ecosystem management and for the resilience of human communities.

Keywords: climate change, sea level rise, coastal archaeology, vulnerability, catastrophic events, Puerto Rico, Hurricane Maria

Introduction and Problem Placement

Climate change threatens thousands of coastal cultural heritage sites globally (Bird 1992; Dawson 2016, 2013; Ezcurra and Rivera-Collazo 2018; Fitzpatrick 2012; Hambrecht and Rockman 2017; Ives et al. 2018; O'Rourke 2017; Reeder et al. 2012; Reeder-Myers 2015; Rick and Fitzpatrick 2012; Rockman 2016; Sesana et al. 2018). Potential impacts to the stability and permanence of sites include coastal and alluvial erosion (Peres and Deter-Wolf, 2018; Reeder-Myers, 2015; Reimann, 2018), landslides and land movement (Tarragüel et al. 2012); melting of permafrost and its related backshore slumping (O'Rourke 2017); changes in microbial activity and acceleration of organic degradation (Hollesen et al. 2018); incidence of wildfires (Mallinis et al. 2016), modern development, infrastructure adaptation projects, migration, and relocation of vulnerable populations in the present (Anderson et al. 2017); looting after sites become exposed during catastrophic events (Peres and Deter-Wolf 2018: 295). The speed at which these changes and impacts can happen has made archaeologists painfully aware of how vulnerable the archaeological record is and how fast it is disappearing.

Destruction of archaeological sites and tangible cultural heritage is not a problem solely relevant to archaeologists or heritage professionals. Cultural heritage and local knowledge are integral to reducing social vulnerabilities and increasing community resilience to climate change (Hardy et al. 2018; Rockman 2012; Thomas et al. 2018). Place grounds communities by providing shared locality, shared identities, and localized community well-being, resilience and

public health (Adger et al. 2011; Cox and Perry 2011; Mayes 2018). In the context of landscape- and environment-altering sudden catastrophes or slow disasters, the distress and disorientation caused by unexpected change to place—this being caused by forced migration as climate refugees or by landscape rearrangement after flooding, erosion or landslides—exacerbates the fragility of communities. At the same time, the presence of tangible cultural heritage can help re-ground disoriented communities, contributing to the reorganization and restructuring of local resilience (Cox and Perry 2011; Crane 2010). In the context of disasters, documenting and engaging with cultural heritage, in collaboration with communities, is a path towards supporting local community resilience because it helps affected groups to re-ground with their past, their local histories, and their local knowledge after chaos (Peres and Deter-Wolf 2018). In the case of coastal communities, not only the physical survival of individuals and the location of their houses are at risk; but also the material evidence of their place, that which binds the history of communities to specific places, is being lost forever as sea level rises, coasts erode, and archaeological sites are washed away.

In response to the palpable threat, many archaeologists and other heritage professionals have actively engaged with the search for solutions to mitigate damage (see discussion in Hambrecht and Rockman 2017). One of the first steps forward is usually conducting vulnerability assessments that tap into already available cyber-infrastructure. This article focuses on the reliability of desk-based vulnerability assessments after a climate change induced catastrophic event.

Just before Hurricane Maria, Ezcurra and Rivera-Collazo (2018) assessed the threats posed by climate change to Puerto Rico's heritage considering the local forecasts of change. In addition to more extreme weather events and higher intensity storms, climate change impacts to Puerto Rico's cultural heritage include: changes in precipitation, with heavier and more intense

rainfall occurring in many regions; increased air and sea surface temperatures; increased acidification of the ocean; increased rates of erosion from wind, floods, and wave action; and flooding caused by sea level rise (SLR). The study concluded that these impacts will affect tangible heritage in many ways: exposed artifacts will undergo higher rates of deterioration; some organic materials will decay faster; wooden structures will become more susceptible to swelling, warping, or cracking; the ground around structures will erode, reducing site stability; buried materials exposed to increased wetting and drying will experience faster rates of decay; and extreme weather and storm events will cause sudden damage, including structural collapse, pipe failure in historic buildings, the collapse of walls from flooding, increased rates of erosion, and the flooding of museums, archives and deposits of archaeological and historical objects. In addition to the risks to heritage on land, archaeological remains in marine environments will be at risk of wave erosion, decomposition of organic material, corrosion, rust, and structural damage (Ezcurra and Rivera-Collazo 2018: 199 - 202).

The study then specifically assessed the risk that the expected rise in sea-level by the end of the century poses to the coastal heritage of Puerto Rico. The SLR data was obtained from NOAA's projections (coast.noaa.gov/digitalcoast/tools/slr) as values of 0 to 1.8 m in increments of 0.3 m. For the cultural data, the study used the record of all archaeological sites below 20 m in elevation in the National Register of Archaeological Sites of the Institute of Puerto Rican Culture (known as ICP in Spanish). For assessment, the study mapped the sea-level rise dataset onto point data of individual sites to determine the number of sites at-risk of inundation at and within 1 m above the projected highest high tides for 2050 and 2100. Using the ICP database, Puerto Rico has a total of 1,185 known archaeological cultural heritage sites between 0 and 20 m in elevation (Figure 1). Of the overall 1,185 sites, 555 are historic, 534 are indigenous, 48 are multi-component, and the remaining 48 are of unknown cultural affiliation. Of these sites, 27 are

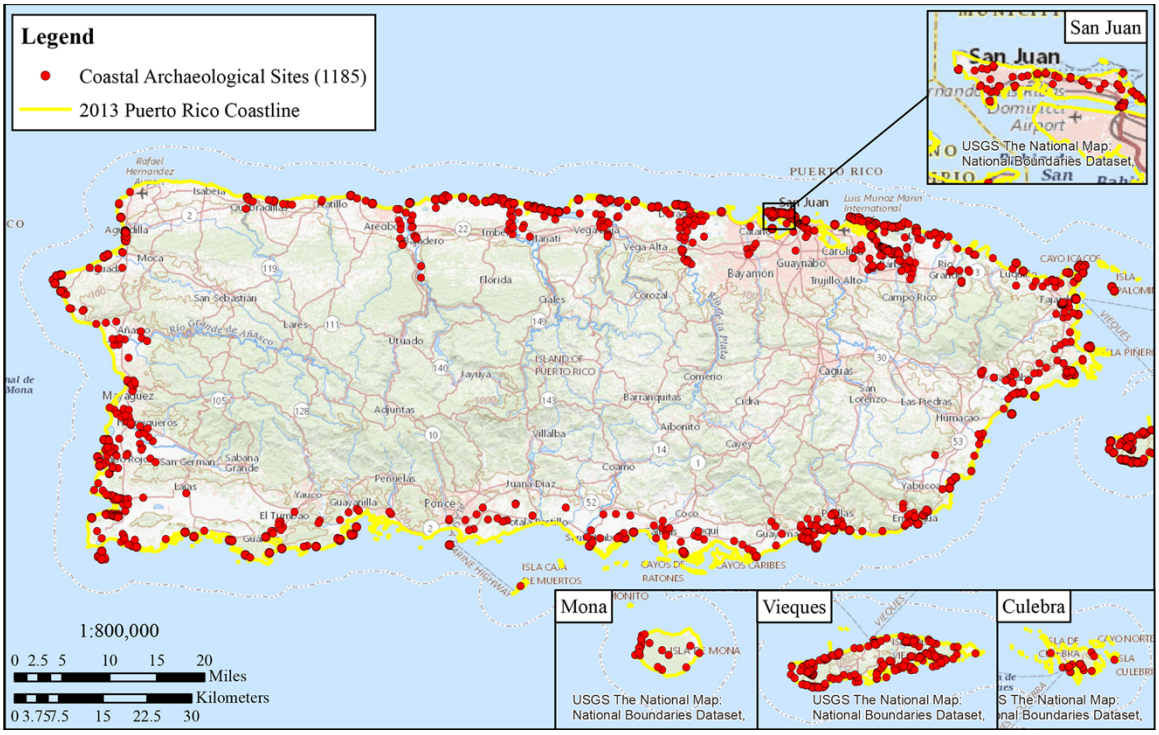

Figure 1: Archaeological sites of Puerto Rico between 1m - 20m above sea level, registered in the inventory of archaeological sites of the Institute of Puerto Rican Culture (provided by the Program of Archeology and Ethnohistory in 2017). Map prepared by Eric Rodriguez.

already inundated at high tide today. An increase of 0.6 m in sea-level (conservative projections for mid-century) will inundate 56 sites at the highest high tide in Puerto Rico. An additional 69 sites lie within 1 m above the 2050 hightide line. The number of inundated sites jumps to 140 with a 1.8 m projection in SLR (estimate for the end of century). An additional 148 sites lie within 1 m of the 2100 high tide line (Ezcurra and Rivera-Collazo 2018:202 – 203).

Hurricane Maria hit Puerto Rico in September 20 and 21, 2017 as a storm category 4 bordering on category 5. Acknowledging the potential damage to cultural resources, a coastal survey was developed in February 2018 to assess the impact of wave activity over archaeological heritage on a section of the north coast where the hurricane eye made its exit, along the Manatí – Barceloneta coast of Puerto Rico. The inspection started at the Los Tubos beach, just north of Tortuguero Lagoon (18.4692°, -66.4554°) and ended at Puerto Las Vacas site, at the Palmas Ward of Barceloneta (18.4872°, -66.5523°), for a total study area of 11 linear kilometers (Figure

Figure 2 Study area on the north central coast of Puerto Rico. The area was subdivided in 6 sections: 1) Palmas to La Boca, 2) HLE Nature Reserve, 3) Poza de las Mujeres to Las Palmas, 4) Mar Chiquita, 5) Los Tubos Mountain Bike Trail, and 6) Tortuguero/Los Tubos Beach. Methodologically, survey was conducted from East to West, beginning at the Los Tubos beach in Manati and ending at the Puerto Las Vacas site in the Palmas Altas ward of Barceloneta. The description of the results however, is organized from West to East, starting with Puerto Las Vacas.

2). This survey focused specifically on the coast line, given that preliminary coastal impact assessments so far have shown lower beach-face gradients, intense erosion of sand dunes throughout sandy beaches (Alvarado León 2018a) and impact to off-shore reefs that normally would have reduced the wave energy reaching the shore (Alvarado León 2018b). These changes present a significant threat to coastal sites exposing them to more flooding and heavier wave impact. Before Maria, a total of 10 sites had been reported along the coastline of the study area (Table 2) and are included in the register of the Institute of Puerto Rican Culture (ICP). For this survey, we inspected all known sites and conducted walk-over surveys of all accessible coastlines to investigate if additional sites had been exposed.

Methods

Survey consisted on a straight-line walkover of the coastline and adjacent land focusing on areas exposed to wave action. When sites were identified, assessment included description and GPS positioning of sites, and photographic documentation of archaeological artifacts, their context, and taphonomical interpretation. Aerial images (https://storms.ngs.noaa.gov/storms/maria/index.html#7/18.056/-64.824) were used to gauge the visible changes to the landscape before

Table 1: Criteria for site assessment. The assessment criteria include field evaluation of observed conditions. The ranked values are a perceived, qualitative, ranked measure—from low to very high—of the three main variables. Including a Prioritization for Intervention is based on the SCAPE model (Dawson 2013, 2016). The criteria included in Level of Threat is based on Reeder-Myers 2015.

Variable	Assessment criteria	Assessment Ranked Values
Site importance	Potential of the site to provide transformative knowledge. For example, the site has excellent context, deep chronology, and/or represents important historical events	**Low**: site will contribute nothing new **Very high**: Site has the potential to completely transform what we know if the history and pre-history of the study area
Level of Threat	Physical threats affecting the location. Criteria to be considered include: Geomorphology; Coastal Slope; Distance to shore; Wave height as witnessed during inspection; and Historical wave energy patterns	**Low**: Site is safe. The geomorphology is solid rock with low potential for sudden erosion, the slope gradient is steep so that sea level rise will not necessarily reach it, site is away from the shore, waves are low, and there is no recurrent pattern of high energy waves impacting the area. **Very high**: Site is at risk. The geomorphology is loose sediment with high potential for sudden erosion, the slope gradient is low so that sea level will easily overcome and flood the location, the site is on the shoreline or very close to it, waves are high, and there is a recurrent pattern of high energy waves impacting the area.
Priority for Intervention	Combination of research potential and level of threat	**Low**: the site is not at risk or has of low importance **Very high**: the site is at high risk and is highly important.

and after the event. Loosely following the SCAPE model (Dawson 2013, 2016), site assessment included a ranked valuation—from low to very high—of site importance, level of threat from coastal erosion, and priority for intervention (Table 1). Site importance considers what the potential of the site is to provide transformative knowledge to the archaeology and history of

Table 2: Sites included in the register of the Institute of Puerto Rican Culture (ICP) for the study area.

Site	Name	Study Zone	Location	Type	Chronology
MT-1	Los Tubos	6	Tortuguero / Los Tubos	Petroglyph	Pre-Columbian
MT-10	Tortuguero	6	Tortuguero	Site	Pre-Columbian
MT-26	Los Molinos 2	5	Los Tubos Nature Reserve	Site	Pre-Columbian
MT-25	Los Molinos 1	5	Los Tubos Nature Reserve	Site	Pre-Columbian
MT-21	Punta Boquilla	3	Las Palmas Beach	Site	Pre-Columbian
MT-36	Punta Boquilla	3	Las Palmas Beach	Unknown, possible petroglyphs	Unknown
MT-3	Poza de las Mujeres	3/2	Caño Boquilla (Hacienda Esperanza Nature Reserve)	Site	Pre-Columbian
MT-7	Tierras Nuevas	2	Playa Machuca	Site	Pre-Columbian
BT-7	Hallazgo 1	1	Boca	Site	Pre-Columbian
BT-25	Puerto Las Vacas	1	Palmas Altas	Site	Pre-Columbian

Puerto Rico and the Caribbean. Level of erosional threat considers the local coastal conditions and the potential for the site to suffer further erosion. Priority for intervention considers the site within the context of research and combines its research potential and risk of disappearance to adjudicate values to priority for intervention before the sites are washed away.

Data were recorded digitally. Full walk-over survey was conducted, from west to east, in Palmas and Boca Wards of Barceloneta from Puerto Las Vacas to La Boca; along the coast of Hacienda La Esperanza (HLE) from Machuca to Caño Boquilla; from Poza de las Mujeres to Las Palmas Beach; and along a section of Los Tubos / Tortuguero beach (Figure 2). Other known sites were deliberately searched for and inspected. The area around Mar Chiquita was not visited because none of the sites are at the shoreline, and development in the area interrupts

accessibility. The survey benefited from the participation of two citizen scientists experienced in archaeological survey: Hector Rivera Claudio and Hector Rivera Robles.

Limited follow-up visits to further document the process of change after impact were conducted by the author in June 2018 and by the citizen scientists in October 2018.

Results

Results are organized geographically from west to east in the following sections: 1) Palmas to La Boca; 2) HLE Nature Reserve; 3) Poza de las Mujeres to Las Palmas; 4) Mar Chiquita; 5) Los Tubos Mountain Bike Trail; and 6) Tortuguero/Los Tubos Beach (Figure 2). While the aerial images helped identify the magnitude of overall geomorphological change after the storm, as well as areas of most severe impact, the sites themselves and the damage they suffered are not readily visible in the images, reason for which field visits were indispensable. Presentation of results includes a qualitative assessment of the site importance, level of threat from coastal erosion, and priority for intervention.

Section 1: Palmas to La Boca, Barceloneta

The ICP inventory reports two coastal sites within this survey area: Puerto las Vacas (BT-25) and Hallazgo 1 (BT-7).

Puerto las Vacas (BT-25)

This site was known to have been impacted during Hurricane Maria. Photos of large ceramic fragments had been published in local media (Alvarado León 2017a, 2017b), and local agencies (Institute of Puerto Rican Culture, State Historic Preservation Office, and Department of Natural Resources) were activated to curtail looting.

Inspection revealed severe impact to the site. *In situ*, stratified, deposits begin at the start of the survey area and continue in stratified layers between 0.5 and 2 m below the top of the dune

for a distance of ca. 600 m towards the east. Three ca. 2 m long looter pits were evident at the beginning of the observed deposits. Large pottery fragments were seen within eroded sand collapsing from the dune. The historic Camino del Rey, initially reported by archaeologist Marisol Meléndez during a contract archaeology project in Palmas Altas, was also identified in the eroded profiles. Some of the layers of Puerto Las Vacas are very thin. Cultural layers can be distinguished from dune sediments due to the abundant presence of small pebbles, what seems to be organic matter providing cohesion to the sand, and sometimes abundant food remains (crab and mollusks). Considering the large extent of this site, it is possible that it continues towards the west, merging with Punta Palmas site (BT-5), just 450 m to the west, making both these deposits a single, very large, settlement. Based on the location of collapsed palm trees, it is estimated that the storm surge eroded the dunes back 1–2 m, and possibly more in some locations.

Site importance: high

Level of threat from coastal erosion: very high

Priority for intervention: very high

Hallazgo 1 (BT-7), La Boca (BT-6)

The BT-7 site was reported by Marisol Melendez as Ostionoid pottery eroding on the coastal profile and impacted by construction. Considering location and cultural contexts of the finds, I propose that BT-7 should be considered to be part of the La Boca site (BT-6). This site is located near or under the baseball park in the Boca community, inland from the seashore. The specific center of the deposit was not inspected as it is not currently under threat by wave action. At B-7, inspection identified *in situ* pottery under construction fill within a clayey layer. It is evident that the area was heavily impacted by storm surge. It is unknown how much land-surface or materials were lost during to erosion.

Site importance: medium

Level of threat from coastal erosion: high

Priority for Intervention: low

Other finds

No other ancient, culturally-relevant, anthropogenic materials were identified in between Puerto las Vacas and Boca, but a significant amount of buried trash (including metal, plastic bags, and many other remains) were evident along the way, especially near houses. Based on the types of artifacts visible, it seems the trash was accumulated in the 70s and 80s. This debris, within eroded dune profiles and exposed to erosion from the waves, constitutes a source of contamination, and poses a severe risk for local ecosystems.

Section 2: HLE Nature Reserve

Hurricane Maria's storm surge caused devastating damage to the sand dunes throughout the nature reserve. Exposed vertical dune profiles were observed to a height of over 2 m in some locations. The areas immediately behind (southward of) offshore aeolianite ridges suffered less damage than those exposed to the full force of the storm surge. The ICP database reports two coastal sites, Tierras Nuevas (MT-7) and Poza de las Mujeres (MT-3), within the HLE Nature Reserve. MT-3 will be discussed as part as the new finds in this survey section.

Tierras Nuevas (MT-7)

Inspection revealed impact to Tierras Nuevas, the only known well preserved ceremonial site with multiple ball courts on the northern coast of Puerto Rico. Tierras Nuevas includes six ball court plazas and six mounds. It is located on a flat esplanade between a very tall fossilized sand dune and the sea, and immediately to the east of the Manatí River mouth. The original substrate is red sandy clay. The site was not flooded by the river or by waves during Hurricane Maria. However, the northern extent of the site was severely impacted by wave activity, which stripped

away most of the sand covering the ancient soils on which the site is located. The north-western-most mound of the site (Mound A), located just north of Plazas 4 and 5, received the heaviest burden of the wave action. In this area, high density of pottery and artifacts were exposed on the red clay and brown loam. Eroded pottery fragments were observed at the swash zone about 250 m to the east of Mound A for a distance of ca. 300 m of beach front. While it is possible that at least some of the fragments originated from unidentified submerged deposits, micro-local waves and current direction suggest that the fragments most probably were transported from the eroded Mound A. No other areas of *in situ* materials were identified adjacent to Tierras Nuevas.

The level of erosion at the coastal portion of the site is extremely significant. Clay was exposed for a length of over 200 m of beach front and beach face. The clay contains rhizoliths, but no *in situ* artifacts were identified (except for the area of Mound A). Interestingly, erosion exposed a break in the horizontal clay profile, which contained sand and large rocks. This area seems to correspond to the space between Mounds B and A, and deserves further investigation to evaluate if it is natural or anthropogenic. While, aside from Mound A, there is no evidence to support that the site was severely disturbed by storm surge, the new exposure of the clay basal layer to constant wave action constitutes a severe threat to the site, as the mobile sand buffer was removed and now the clay is being washed away. It can be expected that constant wave action over the clay will eventually threaten the site itself, particularly Mounds A, B, and Plaza 1, as well as other features we still have not identified. Mitigation action plans must be designed and implemented immediately.

Site importance: very high

Level of threat from coastal erosion: high

Priority for Intervention: very high

New find: sandstone quarry

Inspection of the coastal area revealed historic mining of sandstone rock to the east of Tierras Nuevas. Rectangular-cut sandstone blocks can be seen underwater in the cove created by the fossil dune. Cut sandstone blocks had also been identified within the local forest in a previous informal survey in 2013. Storm-triggered erosion exposed train tracks reaching the beach with a cut block immediately adjacent to it. The context suggests that most of the production process—from tool marks, cutting and shaping, to block extraction system—is evidenced in the location and deserves further analysis.

Site importance: high

Level of threat from coastal erosion: low

Priority for Intervention: low

New (possibly submerged) site – Oubao Moin

The area to the east of the quarry was littered with Pre-Columbian pottery at the top of the swash zone, marking the wave-swash shape. Detailed inspection showed that the pottery in the area is angular – indicating little or no long-distance transport, and therefore local provenience of the archaeological remains. Coralline algae was observed to be covering some of the larger fragments. The presence of this type of biogenic carbonate cover on archaeological objects indicates that the material was exposed on the shallow sea bottom for an extended period of time before being removed and transported to the beach face. An informal underwater inspection of the shallow submerged area of the beach zone demonstrated the presence of *in situ* pottery and exposed clayey deposits beneath the sand cover.

The Ciudadano Científico archaeological survey (2012 – 2015) (Rivera-Collazo, Rodríguez-Franco, and Garay-Vázquez 2018) identified a rock shelter with undiagnostic pottery fragments, food remains, glass and metal fragments in this area only ca. 150 m south from the location of the deposit. No cultural remains had been identified on the coastal portion of this area

Figure 3: Impact of Hurricane Maria to the coastline. The red arrows mark the points where the coastal flooding breached the local sand dunes. Details are cross referenced in the text. The letters mark the location of archaeological contexts: a) marks the area of the possible new submerged site and the rock shelter near it, b) is Cueva Golondrinas and Playa de las Mujeres, and c) is the area of Sitio Botones (see text for explanations). The background photos are oblique and nadir imagery that was acquired following Hurricane Maria in September 2017. The aerial photography missions were conducted by the NOAA Remote Sensing Division. The images were acquired from an altitude of 2500 to 5000 feet, using a Trimble Digital Sensor System (DSS). The original zip files and imagery is available at https://storms.ngs.noaa.gov/storms/maria/index.html#7/18.056/-64.824.

before, even after a systematic surface survey in 2014, and regular beach walk-overs since 2011. This indicates the possible presence of *in situ* submerged or buried archaeological remains at this location that was negatively impacted by Hurricane Maria. Additional assessment is required, but, if corroborated, this would be a new archaeological site identified within Esperanza Nature Reserve, which was preliminarily named Oubao Moin. Further analysis is needed to determine: 1) the context and extent of the resource; and 2) its relationship with the rock shelter discovered earlier.

Site importance: unknown

Level of threat from coastal erosion: high

Priority for Intervention: high

Caño Boquillas

Hurricane Maria caused severe flooding of the coastal plain behind the coastal sand dunes. River flood waters, which reached over 3 m high in some areas, were held back by the severe storm surge, exacerbating in-land coastal flooding. The presence of the Barceloneta levees on the West of the floodplain prevented that town from flooding, but the water expanded east towards la Poza de las Mujeres. Even though the main Grande de Manati River channel deepened, and its mouth sand bank was flushed away, this was not enough to allow all the flood water to empty towards the ocean. Water pressure on the Manati side of the flood plain built behind the unconsolidated or semi-consolidated coastal sand dunes and wetland drainage points, eventually bursting through at four main points: 1) 18.479125° -66.515689°; 2) 18.477659°, -66.513222°; 3) Caño Boquilla; and 4) Poza de las Mujeres (Figure 3). While drainage points 3 and 4 were already existing wetland drainage areas, these deepened and widened significantly during the flood. Erosion at Point 4 impacted an archaeological deposit to be discussed further ahead (Study Area 3). Points 1 and 2 used to be stable sand dunes but the flood flushed them away. Eroded (Pre-Columbian) ceramic fragments were observed at the swash zone immediately to the east of these two new drainage areas. Based on the observations already discussed at Tierras Nuevas, it seems that this pottery was transported from a western point of origin, possibly being carried through the dunes with the flood water. No pottery was observed *in situ* within the exposed dune profiles. Further survey must be conducted to identify the source of these fragments.

Site importance: unknown

Level of threat from coastal erosion: unknown

Priority for Intervention: unknown

Poza de las Mujeres, MT-3 / Cueva Golondrinas

This site is identified in the ICP inventory as pre-Columbian. This site was investigated in the mid-20th Century by Irving Rouse and others (Rouse 1952; Rainey 1940). Cueva Golondrinas consists of a narrow rock shelter with abundant pottery and food remains. No petroglyphs were seen in the location. Poza de las Mujeres is a habitational site further to the east of this location, outside Esperanza Nature Reserve.

Neither Poza de las Mujeres nor Cueva las Golondrinas were inspected during this study because the flooding at Caño Boquillas and Poza de las Mujeres drainage respectively (Points 3 and 4 defined above) impeded access. Even though this location was not inspected, it is protected by the aeolianite (relic sand dune) on the coast, and therefore, it might not have suffered direct impact from the storm surge.

Site importance: medium

Level of threat from coastal erosion: unknown

Priority for Intervention: unknown

Section 3: Poza de las Mujeres to Las Palmas

The most severe damage that Hurricane Maria caused to this location was the erosion of Poza de las Mujeres, at the westernmost part of this study section, as the flood-waters opened the wetland's drainage channel, washing away an access road, coastal dunes, a house that had been built on the sand dunes, and leaving four other houses uncommunicated. The ICP inventory identifies two sites at the coastline within this study zone: MT-21 (Punta Boquilla) and MT-36. In order to continue the geographical coherence of the results description, MT-21 and MT-36 will be discussed after the results of the western section of the study zone, where no archaeological deposits are included in the ICP inventory.

Sitio Botones, Button Industry refuse

As mentioned above, drainage of the coastal flood impacted the sand dunes and structures at Poza de las Mujeres. By eroding the sand deposits at the mouth of the Poza de las Mujeres wetland, this erosion washed away coastal sands and exposed a large deposit of industrial refuse associated to a historic shell button industry (possibly first half of the 20th Century). Most of the production process is evidenced in the deposit, from shells, to button stubs, button blanks and buttons with threading wholes. The refuse is mostly concentrated on discrete massive layers within a mound that was cut in half by the erosion. Additional scattered refuse can be seen along a large area, to the east, south and west of the mound, including to the west of the uncommunicated houses about 400 m west of the mound. This discovery places Puerto Rico within a global button market with similar refuse contexts as far as US (Tennessee and Connecticut) and Israel (Acre and Jerusalem) (Ktalav 2015). The erosion during Hurricane Maria washed away half of the mound, exposing over two meters of refuse stratigraphy; and disconnected the deposit on the east and west sides of the area where refuse has been identified. Given the scale of erosion and landscape change caused by the force of the water flowing through this area during the event, and the fact that this site had not been reported or studied, it is impossible to know the extent of the damage.

Site importance: high

Level of threat from coastal erosion: very high

Priority for Intervention: very high

Las Palmas (Punta Boquilla Site MT-21)

Inspection at Punta Boquilla showed no archaeological remains at the shoreline, nor evidence of flooding or wave activity further in land. There is nothing to suggest that Punta Boquilla was affected by the Hurricane. However, debris clearing activity with heavy machinery did impact

the surface of the site. This anthropogenic activity post-hurricane has been more damaging than the storm itself.

Site importance: high

Level of threat from coastal erosion: medium

Priority for Intervention: low

MT-36

The ICP inventory only reports a code for this location, and it is possible that it consists of a small rock shelter with petroglyphs. Inspection failed to identify archaeological remains in the reported location. More detailed inspection is needed to locate this site.

Site importance: unknown

Level of threat from coastal erosion: unknown

Priority for Intervention: unknown

New site: Las tres caras

This site was recently discovered by one of the citizen scientists affiliated to the project, Hector Rivera-Robles. Even though the site was not under threat by the hurricane, it was included in the survey. The GPS data revealed this is a new site, not included in the ICP inventory. The site consists of a very small rock shelter: the entrance is about 60 cm wide with a maximum height within the shelter of ca. 80 cm, and a maximum depth of ca. 4 m. Immediately at the entrance of the shelter there are two petroglyph panels facing each other. The northernmost assemblage consists of a panel of three anthropomorphic characters looking towards the opposite wall where the other two carvings are located. Of these other two carvings, one is a large face with a headdress and occupies a very dominant location clearly visible form the shelter's entrance. The second is hidden behind this one and presents no clear anthropomorphic identification. The

three-character panel has been identified before in other settings, most recently reported by Raymond Feliciano in the petroglyphs of El Yunque Rainforest.

Site importance: high

Level of threat from coastal erosion: none

Priority for Intervention: low

Section 5: Los Tubos Mountain Bike Trail

The coast line of this study zone was not visited because erosion made it too dangerous to access the area from the east, and private properties block the path from the west. Assessment from the top of the area within the Los Tubos Mountain Bike Trail revealed severe sand erosion at the coastline, exposing rock at the seashore where a wide sandy beach is visible in the aerial photographs. Two sites are reported in the ICP inventory for this zone: Los Molinos 1 (MT-25) and Los Molinos 2 (MT-26). No new sites were identified.

Los Molinos 1 (MT-25)

This site could not be located in the field. It is possible that the deposit lies within the heavily forested area to the west of the path we used to access the location or at the base of the cliff on the beach. However, regular beach inspection along that shore by volunteer Rivera-Robles has not revealed archaeological remains in this area.

Site importance: unknown

Level of threat from coastal erosion: low

Priority for Intervention: low

Los Molinos 2 (MT-26)

This site consists of a habitation area with archaeological remains scattered on the surface. There is not enough information regarding patterns of distribution of materials within the site. A visit to

the site in 2015 showed it to be at the top of the rocky outcrop, overlooking the sea. A layer of rubble fill had been deposited over the site, apparently to support modern use of the area. Hurricane Maria caused damage to the site, mostly by water erosion and uprooting trees. However, the most significant damage to this site is the constant beach-ward flow of recreational mountain-bikes running over the slope containing the densest concentration of pottery sherds. A decrease in slope gradient is evident along the area where the bikers access the beach. Trail maintenance activity using heavy machinery, including what seems to be clearing activities to remove downed vegetation, seems to have impacted the area, as evidenced by the exposed ceramic fragments on the surface an ca. 85 m long area. Wave activity eroded the coast and it is possible that some part of the archaeological site washed out to sea. However, conditioning of the area for mountain-biking (adding gravel and clearing the area with heavy machinery) seems to have caused more damage to the site than the hurricane itself.

Site importance: unknown

Level of threat from coastal erosion: medium

Priority for Intervention: medium

Section 6: Tortuguero / Los Tubos Beach

The walk-over survey of this area was conducted from east to west starting at 18.4692°, -66.4554°. This study area consists of a series of very large boulders buried under several meters of sand that shapes the general morphology of the storm terrace and beach face. A road separates the beach from the Tortuguero Lagoon immediately to the south. No significant change was observed to this beach after Maria, although new sand deposits were observed on the south portion of the road. Two archaeological sites (Los Tubos MT-1, and Tortuguero MT10) are reported for this study area in the ICP register.

Los Tubos (MT-1)

This site is reported to consist of petroglyphs, but no further data is available. The GPS coordinates provided by the ICP for this site place them within the forested area, south of the road, near MT-10. Inspection of this area revealed no archaeological materials. No coastal petroglyphs were identified north of this location either, although three separate panels were observed further to the east (see below). If there are petroglyphs in this area, it seems there were not directly affected by the storm.

Site importance: unknown

Level of threat from coastal erosion: unknown

Priority for Intervention: unknown

Tortuguero (MT-10)

According to the ICP records, this site consists of a habitation area with dense food refuse, pottery and possibly one plaza/ball court. There is no additional information. Surface observations on and around the coordinates provided by the ICP revealed no archaeological remains. It is possible that sand transported during the storm partially buried the site. However, it is also possible that more detailed inspection is needed given that the area was not inspected in high detail, as first priority was given to the shoreline.

Site importance: unknown

Level of threat from coastal erosion: low

Priority for Intervention: medium

New finds: Petroglyphs panels

Several petroglyph panels have been identified in this area since 2013. These carvings are usually not visible because they are located under the sand at the low-tide swash zone. Only two

of them were (partially) visible on the days of inspection. One of the panels was exposed for only one hour during the lowest low-tide witnessed during inspection. This time frame allowed for the acquisition of a high-resolution photomosaic in between waves. We expect to be able to construct a 3D model with the images in the near future. Additional petroglyphs were partially uncovered further east on the day of inspection but could not be properly documented due to intense wave action and sand mobility.

Site importance: high

Level of threat from coastal erosion: high

Priority for Intervention: high

Follow-up visit in June 2018

A limited follow-up visit was conducted in June 2018. The goal of this visit was to monitor the severely damaged sites of Puerto Las Vacas and Tierras Nuevas, to sample Sitio Botones, and to assess Oubao Moin. Additional monitoring visits were conducted during Fall 2018 by the citizen scientists affiliated to the project.

Puerto la Vacas

The visit revealed further severe erosion caused by the winter storms, in particular the March 2018 nor'easter storms, which further eroded the sand dunes 6–8 m southward. This erosion impacted residential and recreational structures of the local community causing the collapse of some of them towards the sea. The density of archaeological materials was observed to have decreased significantly. The looter pits were washed away. The citizen scientist Hector Rivera-Claudio visited the site again in October 2018 and reported no visible archaeological remains.

Tierras Nuevas

The visit revealed severe wave damage to Mound A and massive erosion of the clay basal layer. Artifacts were found along the beach, including large *manos* and other stone tools. Even further erosion was evident in October 2018, although no archaeological materials were observed on the beach or the clay profiles.

Oubao Moin

A series of test pits were conducted in the land portion of this area. The submerged portion was inspected visually. The test pits revealed *in situ* archaeological materials from the coastline to the rock-shelter identified in 2013 and further to the west. The top of the context varies from on the surface at the westernmost extent of the tested area, to around ca. 30 cm deep towards the east. The deposit is covered by brown sterile silt. Although the materials are still under analysis, preliminary observations report pottery of late Ostionoid style, and possibly some early Ostionoid or late Saladoid styles in the more deeply buried areas. The landward boundaries of the deposit were not identified. The seaward assessment revealed that pottery extends towards the sea and is currently concreted into beachrock deposits. The geomorphology suggests that the shoreline was further north-east from its current location, indicating that the coastal geomorphology has dramatically changed. It is possible that these changes have happened since the site was inhabited, but further geomorphological research is needed. The assessment concluded that the artifacts identified in Oubao Moin seem to be *in situ* and that the site deserves further research. The erosion caused by Hurricane Maria eroded and exposed the northwestern part of the site.

Sitio Botones

The visit revealed heavy sand accretion in the previously eroded area. The lower 50 – 80 cm of the mound observed in February were already buried in June 2018 and the output of the Poza de las Mujeres wetland was already closed. During this visit we proceeded to

systematically sample the shell layers for further analysis. Since summer 2018, aerial photographs show even further sand accumulation.

Discussion

Storm surge from Hurricane Maria affected the study area in several ways: sand dune erosion, sand deposition, coastal (beach) sand erosion, flooding and high energy flood-water flow towards the sea, uprooted trees and vegetation damage. Dune erosion was very intense in areas that were exposed to direct wave impact but was almost negligible in protected areas protected by the relic sand dunes (aeolianites). Some of these areas even seem to have had sand accretion during the storm. The active coastal dunes received the main burden of Hurricane Maria's impact from both land- and sea-fronts, mitigating wave action, and containing the coastal-plain floodwaters. Anthropogenic impacts observed post-Hurricane include rubble and garbage accumulation in and over the sand dunes and clearing of downed vegetation and sand with heavy machinery.

The results of the February survey are summarized in Table 3. Of the 10 target sites, three could not be identified on the survey because of potential problems with the ICP's GPS coordinates, or low surface visibility; and one—Poza de las Mujeres/Cueva Golondrinas—could not be inspected because it remained inaccessible after the storm. This site is one of the two that is considered under threat by sea level rise in the present. The ICP Register places this site in between two aeolianite ridges to its north and south. Based on the field observations of other sites with sandstone ridges, it can be expected that its geographic location protected the site from wave action. All of the remaining known sites (n=6) suffered impact during or after the storm, with the exception of MT-10 (petroglyphs at the swash-zone). These petroglyphs are in an already vulnerable context, constantly affected by normal wave action and changes in sand

Table 3: Updated list of cultural resources within the study area. The table presents the type of impact observed during the survey, and the relative assessment of site importance, threat level and intervention priority.

Site	Name	Results	Importance	Threat	Priority
MT-1	Los Tubos	Not identified	unknown	unknown	unknown
MT-10	Tortuguero	No obvious impact	unknown	low	medium
MT-26	Los Molinos 2	Hurricane and post-hurricane impact	unknown	medium	medium
MT-25	Los Molinos 1	Not identified	unknown	low	low
MT-21	Punta Boquilla	Post-hurricane impact	high	medium	low
MT-36	Punta Boquilla	Not identified	unknown	unknown	unknown
MT-3	Poza de las Mujeres / Cueva Golondrinas	Not accessible	medium	unknown	unknown
MT-7	Tierras Nuevas	Impacted	high	high	very high
BT-7	Hallazgo 1	Impacted	medium	high	low
BT-25	Puerto Las Vacas	Impacted	high	very high	very high
New	Sandstone mine	Exposed	high	low	low
New	Tombolo	Impacted	unknown	high	high
New	Caño Boquillas	Impacted	unknown	unknown	unknown
New	Button Industry	Impacted	high	very high	very high
New	Las tres caras	No impact	high	none	low
New	Petroglyph panels	Partially exposed	high	high	high

budget. While they are actively eroding, the observed degradation cannot be directly linked to Hurricane Maria. Of the 10 known sites, three are considered to be highly or very highly threatened coastal erosion post-Maria, and two face medium level threats. Given the combination of high potential to make contributions, and the threats they are facing, Tierras Nuevas and

Puerto Las Vacas should be at a high priority for intervention to recover information before further damage occurs. Following these, Tortuguero and Los Molinos 2 should be evaluated to improve our understanding of their importance and threats, in order to better decide if additional steps must be undertaken.

In addition to the known sites, survey revealed the presence of six additional sites within the study area, all of which received some degree of impact, except for the Tres Caras rock shelter, which is within a sandstone ridge, away from the waves. While one of these, Caño Boquillas, still needs to be identified and assessed, all sites located on unconsolidated sediments are facing high or very high threats of further damage if no action is taken. The new site Oubao Moin is particularly interesting. So far, no underwater archaeological site had been reported for the area. The presence of a submerged context is evidence of dramatic changes in sea level and must be further researched to assess the context and its potential to make scientific contributions to the understanding of local socioecodynamics. The late 19th – 20th Century Button Industry site, with its potential to inform about the role of the Caribbean in the beginnings of a globalized market, is very promising. While the initial assessment of the site in June suggested that Botones was the most vulnerable site to further erosion and potentially total destruction, longer-term observations demonstrate new sand accretion that is currently re-burying the site.

Finally, coastal erosion not only impacted archaeological sites and the modern coastal communities near them, but also exposed clandestine deposits of rubbish within the sand dunes. These deposits, which seem to have been discarded on the coast during the last part of the 20th Century, are now been eroded and are actively contributing plastic, metal and other contaminants to the open ocean. Post-disaster rubble is also being disposed of on top of or near the dunes.

The study area is of high importance to Puerto Rican archaeology. Research so far is showing high density of sites with wide temporal and typological contexts. The coastal plain of

the hydrological basin of the Grande de Manati River has been inhabited uninterruptedly since the Archaic period (ca. 4.2 kya) to the present (Rivera-Collazo 2015). All sites identified in this survey have a high potential to make significant contributions to the understanding of socioecodynamics in the Caribbean and Puerto Rico specifically because, although archaeological excavations so far have been limited, the cultural landscapes still have excellent context (low-development and therefore relatively low impact to the archaeological record). In addition, three nature reserves within the study area – Tortuguero, Los Tubos and Esperanza effectively protect the area from further damage. In this context, the environmental impacts triggered by climate change, including unexpected changes in human settlement patterns post-catastrophe, pose a very severe threat to cultural heritage.

Conclusion

In 2017—before Hurricane Maria—Ezcurra and Rivera-Collazo (2018), identified 27 sites throughout the island that were considered to be under threat by sea level rise in the present (year 2017) because of their proximity to the high tide mark. Two of the sites from that list are located within the study area for this follow-up assessment: Puerto Las Vacas and Poza de las Mujeres. Given the documented storm surge of ca. 3 m during Hurricane Maria, all sites close to the coast (n=10) were included in this assessment survey of a 11 km coast section on the north-central coast of Puerto Rico, even if not listed as threatened sites. The survey revealed 6 new sites in the study area, increasing the number of coastal sites to 16. Of these, two sites are facing medium threats to further damage due to coastal erosion, four are facing high threats, and two, very high threats (Table 3). The survey increases the number of threatened sites from two to eight. These results constitute a 400% increase of the number of sites threated by sea-level change within the study area in the present. The study area represents only 2% of Puerto Rico's coastline, which

extends for 502 km. The 2017 vulnerability assessment of Puerto Rico's cultural heritage was too conservative.

These results support the observation by Anderson and colleagues (Anderson et al. 2017) regarding the conservative nature of desk-based assessment. The main reason for the error is that the ICP database is incomplete. The second most important source of error is that sea-level rise does not occur as smooth bath-tub flooding until reaching the predicted 2050 or 2100 marks. Climate change entails intensified changes in weather patterns causing erosion and damage well before the marks of higher sea-level stands. Assessments that consider vulnerability of coastal archaeological heritage are imprecise if they do not take into account the process of climate change, including predicted storminess and erosion. This observation was already made by Bird in 1992.

Similar results are to be expected for desk-based vulnerability assessments that: 1) use incomplete or uncorroborated cultural heritage datasets; and 2) do not model the real process of climate change, in the light of changing weather and shifting climate baselines. Researchers working on this type of assessments for their coastlines have to find out a way to account for these processes. Policy makers and governmental officials—such as state and tribal historic preservation officers (SHPO and THPO in the United States)—must be aware that the results of these studies are conservative, the assessment is as reliable as the database, and the damage can be expected to be more severe and sudden than stepped climate change models forecast.

In its Climate Change Response Strategy, the National Parks Service put forth four pillars for the management of protected areas: science, adaptation, mitigation, and communication (Hambrecht and Rockman 2017; National Parks Service 2010; Rockman 2015, 2016). Furthering from these, effective actionable steps must be taken immediately to record these archives of the past before they wash out to sea or are otherwise destroyed by changing environmental

conditions. These actionable steps must include the following: 1) improving and revising site inventories, sharing data, and maintaining working, off-site, up-to-date backups of digital files; 2) assessing and identifying areas with high risk of damage during catastrophic events using existing environmental datasets and models (Reeder-Myers 2015); 3) selecting areas for prioritized attention, and including consultation with local communities in the decision over prioritization for site intervention so that heritage preservation saves knowledge that is locally relevant to the sense of place of threatened communities (Dawson 2013; Dawson et al. 2017); 4) establishing protocols for dealing with catastrophic events that recruit specialists and dedicated volunteers, thus mitigating the work-load of heritage professionals (Peres and Deter-Wolf 2018); 5) developing creative research strategies that collect meaningful data before sites are lost, including information that can be used for long-term monitoring; 6) advocating with land-owners, land-managers, and those of political and economic interests in coastal areas that cultural heritage is necessary to reduce social vulnerability and increase resilience to climate change (Reeder-Myers 2015).

The effects of rapid environmental change linked to unexpected and severe weather events are being felt around the globe, from deadly wildfires in California to melting permafrost and glaciers in the Arctic to storms around the tropics and subtropics and global sea level rise. The suggested actionable steps are applicable in any part of the world. In the case of Puerto Rico, intervention to protect the island's cultural and historical heritage faces resistance when it comes imposed from the top down and does not incorporate or respect local perspectives and concerns. Based on my conversations with other climate heritage specialists and indigenous groups, the same is true elsewhere, and mitigation plans that ignore local interests are likely to have much less success. Along these lines, more diversity is required at all levels of climate heritage conversations, where traditionally under-represented groups can have an equal voice in these

discussions and not simply an acknowledgement of their suffering.

Based on my experience, the main barrier for success is funding. The speed at which climate change is occurring clashes with the traditional process of grant application. Many of these sites and places cannot wait the months or years required for to obtain funding, or the many cycles of resubmission that are often required in a successful grant proposal. In addition to this, disasters directly impact the livelihood and well-being of individuals in many places, so traditional sources of funding are already stretched thin. We—from archaeologists and heritage professionals to communities—need to start looking outside the box for innovative ways to facilitate project development and heritage preservation. In my experience, the most effective way has been to partner with colleagues with similar interests, assist environmental groups with their priorities, and stimulate citizen science. One further consideration regarding climate heritage is that, in most cases, the proposed protocols that arise from the actionable items described above will most likely be implemented when disasters occur. During these events, researchers must be prepared to wait until it is reasonable and safe; help the public beyond heritage; listen to their stories; respect local traditions, cultures, decisions and processes; and protect cultural diversity. Sometimes these situations will pull us away from archaeology itself, into supporting the wellbeing of our partner communities.

Through my work with Puerto Rico before, during, and after Hurricane Maria, I have learned three main lessons. The first is, while it is true that research can help find innovative solutions to wicked problems in the tangible heritage, climate change is happening much faster than anticipated; faster than research can be made. We do not have the luxury of leaving for later the decision of what to do. Secondly, disaster relief efforts mobilize people of different backgrounds to areas that have been severely damaged and are undergoing sensitive recovery and restructuring processes. While many of the relief efforts are well intentioned, many others

take shameful advantage of the situation for their own benefit, ignoring the ethics of interacting with human subjects. At times of disasters, local knowledge is vulnerable to being destroyed during careless relief efforts when traditions are not respected and local solutions are ignored. Lastly, local and indigenous communities are much stronger than most people assume. They know their challenges, history, and problems, and also have the skills to find solutions. Relief efforts should support local empowerment rather than attempting to solve problems identified from an outside perspective with foreign solutions that might not work for the long-term.

Heritage intervention during times of disasters—such as what happened in Puerto Rico during Hurricane Maria, in northern California during the Camp Fire, or in New Orleans during Katrina—can be traumatic. As such, it is advisable that archaeologists, anthropologists, and others working in disaster contexts manage their own mental well-being and seek professional support early to better assist those who need our help.

Acknowledgements

This article would not have been possible without the inspiration and idea-planting of Tom Dawson and the SCAPE team. This research was possible thanks to the strong support and field work of Hector Rivera-Claudio and Hector Rivera-Robles. Thanks to Para la Naturaleza for their partnership, particularly Carlos Torres, Sandra Faría, Belén Rosado, and all the security guards that drove us to and from the sites. Many thanks to Evelyn Dean and to the Laboratorio de Arqueología Ambiental of the University of Puerto Rico for hosting our visit in February, and to the Centro de Estudios Avanzados de Puerto Rico y el Caribe for hosting our June visit. Thanks to Hernán Bustelo and Inbar Ktalav for their ongoing research regarding on the new Sitio Botones and the shell button industry in Puerto Rico. Finally, thanks to UCSD Prof. Janis Jenkins for her advice in several instances that were better understood through the filter of

mental health. This manuscript greatly benefited from the comments and feedback of three anonymous reviewers and Scott M. Fitzpatrick as editor.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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