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Quantifying the impact of human visitation in two cave chambers on Mona Island (Puerto Rico): implications for archaeological site conservation

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Abstract: Recent archaeological research has discovered well preserved historic and pre-Columbian art covering numerous walls inside caves on Mona Island. Human visits can pose a serious threat to the long term conservation of these fragile engravings and paintings by increasing condensation corrosion rates. The quantification of environmental changes to caves related to human visitation is relevant for prediction of condensation corrosion processes and cave site management policies. This study addresses the threat of increased condensation corrosion to cave art. Data collected in two caves show changes in cave air temperature (T), relative humidity (RH) and CO_2 partial pressure (pCO_2) caused by visitation. Based on the environmental observations, cave air exchange times and condensation corrosion rates of different visitor group sizes were quantified. The corrosion rates increase with the number of visitors and also depend on the chamber ventilation characteristics. Periods of visitation might be the only times when condensation corrosion can occur, especially in cave chambers distant from the cave entrance. This evidence points out the need to develop a conservation management plan that takes account of visitation levels to ensure preservation for future generations.

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Mona Island in the northeastern Caribbean (Fig.1) is one of the most cavernous regions in the world (> 200 caves distibuted over just 55km^2; Frank *et al.,* 1998a). The caves are a main attraction of Mona Island and every year approximately 1500 tourists visit the island. Cave visitor groups on Mona range from large cohorts of up to 20–30 people, such as scout groups who may explore the cave spaces for several hours, to smaller groups and individuals, such as hunters during hunting season, archaeologists and other scientists. The Puerto Rican Department of Natural and Environmental Resources (DNER) controls visitor numbers by issuing no more than 100 visitor permits to the island at any one time. However, the activities of people in the caves themselves are subject to little control due to the number of cave sites, their inaccessibility, and the large size of individual caves.

Indigenous and historic cave art as well as *in situ* archaeological artefacts (Fig.2) have been documented in many of these caves (Dávila Dávila, 2003). Current research has so far documented in excess of 30 caves with extensive pre-Columbian cultural sites, and many more with significant historic inscriptions and images spanning the 16th to 19th centuries, making this one of the most significant cultural landscapes in the Caribbean region (Samson and Cooper 2015; Samson *et al.,* 2015). In some caves highly concentrated pre-Columbian wall art is found in single chambers (pre-Columbian chambers) of ceremonial use (Samson *et al.,* 2013; Dávila Dávila, 2003). Mona Island's cave art is significant in terms of understanding human colonization of the Caribbean, inter-island interaction, and key historical periods in the region. The caves are therefore exceptionally well-preserved time capsules of human activity, perhaps unique in the region, and their long term conservation is critical.

Worldwide, human visitation poses a threat to the conservation of unique archaeological cave sites. Well-studied examples include Lascaux Cave in France (Coye, 2011) and Altamira Cave in Spain (Sánchez-Moral *et al.,* 1999). Both of these sites demonstrate that cave art is highly sensitive to changes in cave atmosphere, and that uncontrolled human visitation threatens cave art conservation. Quantitative data covering the potential variables affecting cave art are needed, to help develop effective conservation and management plans. By characterizing the human impact inside a cave prior to its exhibition to the general public (Calaforra *et al.,* 2003), this paper represents a first step towards the protection of Mona Island's vulnerable cultural heritage.

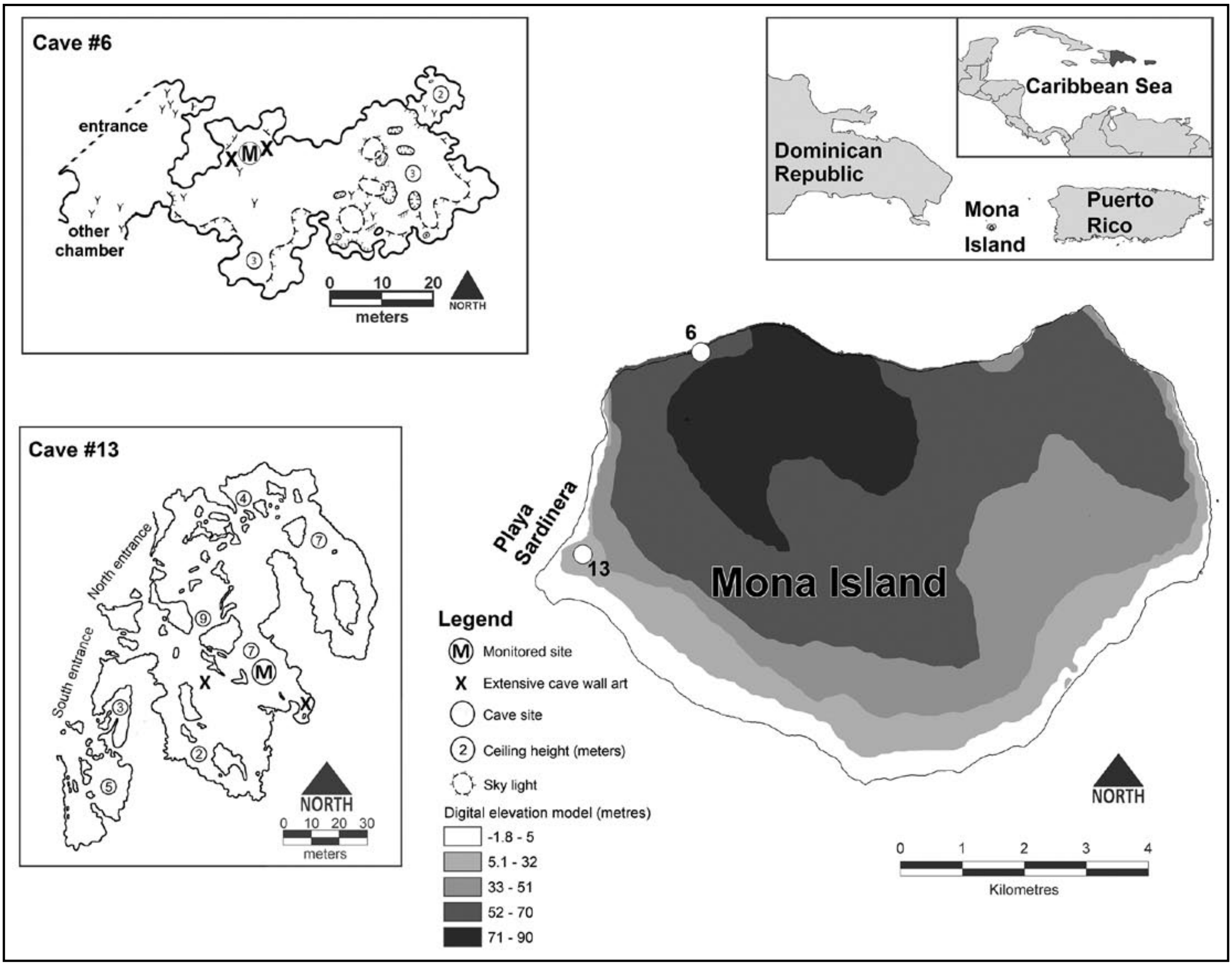

***Figure 1:** Maps showing the location of Mona Island in the Caribbean (top right), Mona Island with the location of both caves (bottom right) and the cave maps of Cave #6 (top left) and Cave #13 (bottom left). The cave atmosphere measurement sites and locations of extensive cave wall art are marked in the cave maps.*

Perhaps the greatest threats to Mona Island's cave art are those of direct destruction by the imposition of graffiti (e.g. Fig.2e), and of intentional or inadvertent human contact with the cave walls. This reflects the fact that the mark-making techniques used in the past include painting and drawing on cave surfaces, and incising into soft cave-wall deposits that are easily damaged. However, other risks include the human introduction of microbial species that colonize the cave walls and cause irrevocably harm to the cave art (Dupont *et al.,* 2007; Cañveras *et al.,* 2001).

More insidiously, and over greater timespans, human visits are known to promote condensation corrosion along cave ceilings and walls (de Freitas and Schmekal, 2003; Miedema, 2009), where undersaturated waters from the warmer cave atmosphere condense along colder cave walls and ceilings, leading to the deterioration of carbonate surfaces (Ford and Williams, 1989). On Mona Island, natural condensation corrosion has been documented close to cave entrances where diurnal temperature variations allow condensation (Tarhule-Lips and Ford, 1998). With increasing distance beyond the cave entrance natural temperatures show no diurnal variations (Gamble *et al.,* 2000). In thermally stable cave environments condensation effects are essentially absent (Dreybrodt *et al.,* 2005). In such situations conditions for condensation might be met only during periods of human visitation, because such visits can increase the cave air temperature by several degrees (e.g. 3°C was documented by Domínguez-Villar *et al.,* 2010). This can threaten the conservation of cave wall art and speleothems (Baker and Genty, 1998) and also increase the rate of deterioration of iron archaeological artefacts (Fig.2d).

Many caves exhibit seasonal and diurnal pCO_2 (carbon dioxide partial pressure) variations commonly linked to variations in ventilation processes (e.g. Spötl *et al.,* 2005; Baldini *et al.,* 2008; Mattey *et al.,* 2010) but the effects of human visits to caves need to be examined more closely (Cowan *et al.,* 2013). Cave visitors exhale air with a CO_2 concentration of 4%, several orders of magnitude greater than the concentration in the natural cave atmosphere. Consequently, high pCO_2 values have been documented in cave atmospheres due to human visitation (e.g. Smith *et al.,* 2013). High cave atmosphere pCO_2 increases the acidity of condensation water due to the formation of carbonic acid (Equation 1; Vouve *et al.,* 1983; Baldini *et al.,* 2006), which raises the water's ability to dissolve carbonate. During cave visitation it has been documented that condensation corrosion increases by up to 78 times (Sánchez-Moral *et al.,* 1999).

$$CO_{2(aq)} + H_2O_{(l)} \rightarrow H_2CO_{3(aq)} \qquad (1)$$

This study focusses upon the impact of human visitation on the cave atmosphere inside pre-Columbian chambers and the resulting implication for condensation corrosion along the decorated cave walls. Changes in the cave air parameters temperature (T), relative humidity (RH) and pCO_2 were monitored in two pre-Columbian chambers during underground archaeological site studies. To discriminate between natural microclimate variability and the visitation-induced changes, the cave conditions were recorded with and without humans working inside the chambers. The cave microclimate results provide a valuable resource to help inform future management of the full spectrum of cave visitation on Mona Island, from touristic to educational and scientific visits. Such management should help to prevent cave art deterioration and the subsequent need for resource-intensive cave restoration (e.g. Dragovich, 1981; Coye, 2011).

Figure 2:
Examples of cave art, archaeological artefacts and recent graffiti in Mona Island's caves:
(A) pre-Columbian painted figure;
(B) historic ship;
(C) finger-fluted cave art;
(D) nineteenth century iron shovel;
(E) an example of recent graffiti.

Methods

Site description

Mona Island is a limestone/dolomite island (6km by 11km) located in the middle of the 140km-wide Mona Passage between Hispaniola and Puerto Rico (Fig.1). It is administered by the Puerto Rico Department of Natural and Environmental Resources (DNER). The island's topography is dominated by a nearly horizontal platform reaching elevations of up to 80m. Its stratigraphy consists of the Lirio Limestone, which overlies the Isla de Mona Dolomite (Frank *et al.,* 1998b). A Pleistocene reef is exposed along the southern coast and the western corner of the island reaching elevations of 6m. At the limestone/dolomite contact numerous flank margin caves are found along the cliff of the carbonate platform. The caves formed due to phreatic dissolution processes along the interface between the fresh water lens and salt water when the pre-Pleistocene island was at lower elevations. Tectonic uplift exposed the caves above sea level (Mylroie *et al.,* 1995). On Mona Island the cave entrances are located along the steep cliffs of the carbonate platform. Their cave geometry is diverse; large cave chambers near the cliff continue into smaller, commonly interconnected, passages a few metres to kilometres in extent – including the longest flank margin cave in the world with 21km of mapped tunnels (Mylroie *et al.,* 1995).

Since their first occupation of Mona Island, at about 2800 BC (Dávila Dávila, 2003), humans have made use of the caves, many of which include chambers with well-preserved decorations along their walls. The cave chambers vary in size (c. 1m – 80m in diameter and c. 1m – 10m in height) and most of them have only one entrance, limiting ventilation.

Ongoing research is discovering new archaeological sites and investigating how and when the sites were used (Samson *et al.,* 2015; Cooper *et al.,* 2016). The cave-wall decorations reveal that one of the periods of most intensive cave use was the pre-Columbian and early colonial period (Fig.2a). During this period extensive and elaborate modification to the cave walls took place through the application of pigments and the extraction of soft cave wall material to create figurative (Fig.2c), geometric and meandering designs ("finger-fluting"). Historic ship graffiti (Fig.2b), pirate markings and marks and artefacts from an intensive period of 19th century phosphorite mining (Fig.2d and Frank *et al.,* 1998a) track the more recent history.

Cave monitoring

Two different cave sites were chosen for the monitoring of human visitation impact on the cave atmosphere. Within the Corazon del Caribe research project (Samson *et al.,* 2015) their cave names have been changed to their database IDs, Cave #6 and Cave #13, to protect against abuse of the caves and to allow consistent reference to each cave throughout multiple publications. The caves were chosen because they are representative of the diverse range of cave systems on Mona Island in terms of their accessibility, cave environment and cave art techniques. They are flank margin caves located on the western and northern cliffs of the island (Fig.1). Cave atmosphere parameters (pCO_2, T and RH) were logged at 5 to 15 minute intervals using a Vaisala GM 70 with a Vaisala GMP222 2000 ppm CO_2 probe and a Vaisala HMP75 humidity and temperature probe. In both chambers the probes were placed on top of a boulder about 1 m above the cave floor, with the sensors extending about 20cm into the free cave.

The cave maps (Fig.1) provide an overview of both the chamber geometry and the cave ceiling heights. Cave #6 is difficult to access and not often visited. It has one main entrance at its west side and three openings in the ceiling in the eastern chamber (sky lights in Fig.1). The cave art is painted. Environmental monitoring in this cave took place inside the pre-Columbian chamber about 30m away from the nearest cave entrance (Map Fig.1). The chamber lies behind a c. 5m-wide passage and opens up reaching about 30m in width and 60m in length with a maximal ceiling height of 3m. Measurements were taken on 14 June 2014 between 10am and 2pm and made on the northern side of the cave chamber where ceiling heights reach up to about 2m and the lower ceiling and wall surfaces are covered by cave art. Two scientists were working in the same chamber from 10am to 11am.

Cave #13, an easily accessible cave on the west side of Mona Island, with two main entrances on its western side (Fig.1). Throughout the human history of the island and up to the present day it has been heavily visited (approximately 1000 visitors per year). In contrast with Cave #6, most of its cave art and historic inscriptions were made using finger-fluting. Its size is more extensive then Cave #6, with ceilings reaching heights of up to 9m and cave chambers that extend more than 100m from the entrance. Measurements were taken in the main chamber, which has ceiling heights of up to 7m and is about 90m from both exits. The measurement site was located 10m in front of a small pre-Columbian chamber (X on the east side in Fig.1), which is extensively decorated with cave wall art. Measurements took place on 16 June 2014 between 9am and 5pm. Two scientists worked inside the pre-Columbian chamber from 9am to Noon. Cave measurements were also taken from 10pm on 17 June 2014 until 7pm on 18 June 2014 to record natural cave environment data. During this period no visitors were present in the cave except to place the instrument and change the batteries.

Chamber air exchange time analysis

Human respiration caused a pCO_2 peak in both cave chambers. The monitoring results show that the CO_2 peak decayed exponentially after the visitation ended until the background value was reached. An exponential decay function was used to estimate the air exchange time for each cave chamber (e.g. Frisia *et al.,* 2011). This was done by simplifying the ventilation process to a linear time invariant system in which the cave atmosphere responded to a step change in CO_2 input. During visitation respiratory CO_2 was exhaled into the cave atmosphere. When visitors left the chamber, the respiratory CO_2 source stopped. The estimation of air exchange times is underlain by two assumptions. Firstly, the CO_2 input into the cave by processes other than human visitation was constant throughout the monitored period and, secondly, cave ventilation linked with the outside air was the only way that CO_2 was removed from the cave. Equation 2 was used to calculate the air exchange time:

$$pCO_2(t) = \{pCO_2^i - pCO_2^f\} * e^{-t/\tau} + pCO_2^f \qquad (2)$$

Where:

$pCO_2(t)$ = pCO_2 at time t [ppm]
pCO_2^i = initial pCO_2 [ppm]
pCO_2^f = final pCO_2 [ppm]
τ = system time constant [minutes]
t = time [minutes]

Results

During human visitation pCO_2 values increased in both caves. In Cave #6 two cave visitors increased pCO_2 by 50 ppm compared to natural conditions, whereas in Cave #13 two cave visitors increased the pCO_2 by 100 ppm (Fig.3). In both cave sites the pCO_2 dropped to natural background values in less than one hour after cave visitation.

Atmospheric pCO_2 values (400 ppm) in Cave #6 were recorded before and after chamber visitation (Fig.3a). During visitation it increased to 450 ppm. The highest T occurred at the beginning of the measurement period. Then T dropped to 24.6°C and rose to 26.9°C in the early afternoon. RH values in Cave #6 ranged from 78% to 89%.

Measurements of the natural conditions without continuous cave visitation in Cave #13 (Log 2 in Fig.3b) showed pCO_2 values slightly above atmospheric values (430 ppm). During visitation and archaeological work in the chamber pCO_2 increase by up to 100 ppm compared to the natural conditions. Natural temperatures were between 24.2 and 24.4°C and natural relative humidity values were always saturated (about 100%). During cave chamber visitation, T increased slightly to 24.6°C and RH values decreased slightly (Log 1 in Fig.3b). The natural conditions (Log 2 in Fig.3b) also showed two disturbances in the T and RH logs. They correlate to brief cave visits to start the measurement and change the batteries (vertical lines in Fig.3b). The disturbances seem to be caused by the brief visits. T and RH are related by Equation 3 (Lawrence, 2005). The rise in T explains the observed RH decrease below 100% because air at higher temperatures can hold more water vapour.

$$RH \approx 100 - 5*(T - T_d) \qquad (3)$$

T is the measured temperature and T_d the dew point temperature in °C. All measurements in Cave #13 during the undisturbed natural cycle showed RH values around 100%. Thus, the undisturbed cave temperature is equal to T_d. Calculating RH using the increased T during short visits explains the measured decrease in RH. It also explains the slight decrease in RH during the archaeological work in the chamber (Log 1 in Fig.3b).

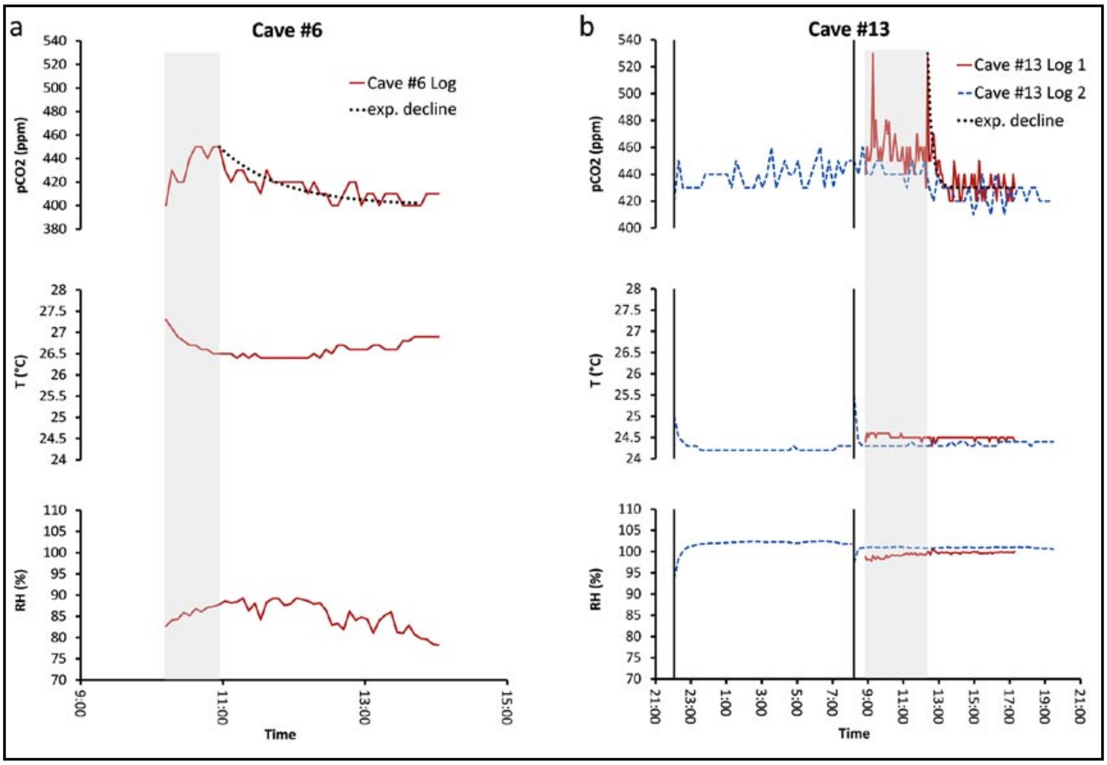

Figure 3:
Results of cave atmospheric logging in cave chambers in Cave #6 (a) and Cave #13 (b), top row shows pCO_2 (top), middle row shows T and bottom row shows RH. Note: The time scale has a higher resolution for Cave #6. In Cave #6 logging took place on 14 June 2014. Two archaeologists worked between 10am and 11am in the pre-Columbian chamber (highlighted period). In Cave #13 Log 1 was recorded on 16 June 2014. It recorded the micro climate change while two archaeologists worked close to the data logger from 9am to noon (highlighted period). Log 2 recorded natural cave chamber conditions without anyone working inside the cave. It was recorded between 17 and 18 June 2014. Both logs (1 and 2) are plotted on the same time scale showing the local 24-hr time of the respective day. During the recording of Log 2 two people were in the cave to start the measurement and change the batteries. The short visits are marked by vertical lines. The black dotted curves show the fitted exponential pCO_2 decline after work ended inside the pre-Columbian chamber in both caves.

In estimating the air exchange time, the moment that respiratory CO_2 input ceased in the cave was chosen as the start point of the fitted curve (t = 0 in Equation 2). The highest pCO_2 reading inside the chamber (450 ppm in Cave #6 and 530 ppm in Cave #13) was set as the initial partial pressure of CO_2 (pCO_2^i). In Cave #13 two short-term spike maxima were recorded (Fig.3b). These might have been caused due to work taking place in close proximity to the data logger. Use of this high value was chosen because it is likely that visitors standing in close proximity to cave-wall art cause similar increases in pCO_2.

In Cave #6 the final pCO_2 (pCO_2^f) was set to 400 ppm, which was the value recorded inside the cave chamber before the work began and after the respiratory CO_2 peak declined (Fig.3a). In Cave #13 it was set to 430 ppm, which represents natural cave conditions without human visitation and also the CO_2 concentration before and after the respiratory CO_2 injection (Fig.3b).

The time constant τ in Equation 2 represents the time it takes to exchange the chamber air volume once with the air outside the cave or with the air in adjacent chambers (cave air exchange time). It was estimated by way of manual curve-fitting (Fig.3) to the measured CO_2 decline for Cave #6 and Cave #13 using the initial and final pCO_2 values mentioned above in Equation 2. The best fit indicates a time constant τ of about 15 minutes for Cave #13 and about 52 minutes for Cave #6.

Condensation corrosion during visitation

In cave chambers where stable cave atmospheric conditions exist, human cave visitation might be the only time when conditions for condensation and, consequently, condensation corrosion are met. Condensation corrosion erodes cave walls when water undersaturated with respect to carbonate condenses on cave wall and ceiling surfaces. On Mona Island, diurnal temperature fluctuations – primarily in the entrance zones of caves – lead to natural condensation corrosion (Tarhule-Lips and Ford, 1998).

Results during the current study show that human cave visitation increases T and pCO_2 in the cave air. Human visits favour condensation corrosion due to the higher temperatures of the cave atmosphere compared to the cave walls. Higher pCO_2 levels cause higher acidity of the condensed water along the cave walls and higher temperatures support faster reaction rates (increased kinetic constant α; Equation 6), increasing the carbonate dissolution rate during the period of visitation.

Theoretical carbonate dissolution rates were calculated for conditions with and without cave visitation, using well-established relationships to T and to pCO_2. The equilibrium calcium-ion concentration (c_{eq}) is a function of both of the above parameters, and limits the theoretical dissolution rate R (Buhmann and Dreybrodt, 1985). A positive R value expresses dissolution and loss of carbonate from the cave wall surface.

$$R = \alpha * (c_{eq} - c) \ \ \mathrm{mmol*cm^{-2}*s^{-1}} \qquad (4)$$

Where R is given in $\mathrm{mmol*cm^{-2}*s^{-1}}$, α is the kinetic constant in $\mathrm{cm*s^{-1}}$, c is the Ca-ion concentration in the water film, which is 0 for condensed water on the cave walls, and c_{eq} is the equilibrium concentration of calcium in $\mathrm{mmol*cm^{-3}}$. R can be converted into dissolution rates ($\mathrm{cm\ yr^{-1}}$) using the following equation (Dreybrodt, 1988):

$$R = 1.174*10^6 * \alpha * (c_{eq}) \qquad \mathrm{cm*yr^{-1}} \qquad (5)$$

The kinetic constant α is a function of T. Between 0°C and 30°C it can be estimated using the following equation (Romanov *et al.,* 2008):

$$\alpha = (0.52+0.04*T+0.004T^2)*10^{-5} \qquad \mathrm{cm*s^{-1}} \qquad (6)$$

Using a transfer function derived by Baker *et al.* (2014) c_{eq} can be calculated from cave T and pCO_2. Baker *et al.* (2014) estimate the apparent Ca concentration (c_{app}), which is the concentration above which carbonate precipitation occurs. C_{app} is c_{eq} multiplied by 1.2 (Kaufmann, 2003). Thus, c_{eq} can be calculated using the pCO_2 and T values measured in the cave. Note that Baker's equation and Equation 7 use the pCO_2 unit *atm*:

$$\begin{aligned} c_{eq} &= 5/6*c_{app} \quad \mathrm{mmol*l^{-1}} \\ &= 5/12*((5.873*pCO_2^{0.2526})+(-0.0167*T+1.5146)) \qquad (7) \end{aligned}$$

# visitors	pCO_2 (ppm)	T (°C)	α (cm/s)	c_{eq} (mmol/cm³)	R (mm/h)	$R_{Visitation}$ (mm/yr)
Cave #13						
0	430	24.3	3.85E-05	8.13E-07	4.20E-05	7.36E-03
2	530	24.6	3.92E-05	8.24E-07	4.34E-05	7.60E-03
Cave #6						
Scenario 1: no temperature increase in pre-Columbian chamber						
0	400	26.5	4.39E-05	7.86E-07	4.62E-05	8.10E-03
2	450	26.5	4.39E-05	7.94E-07	4.68E-05	8.20E-03
Scenario 2: similar temperature increase as observed in Cave#13						
0	400	26.5	4.39E-05	7.86E-07	4.62E-05	8.10E-03
2	450	26.8	4.46E-05	7.94E-07	4.75E-05	8.32E-03

Table 1: *Cave measurements (pCO_2 and T) used to calculate kinetic constant α, Ca equilibrium concentration c_{eq}, dissolution rate R and dissolution per year ($R_{Visitation}$) assuming that weekly cave visits cause conditions for condensation corrosion during 2% of the year. See text for details.*

A pCO_2 rise of 100 ppm and a T increase of 0.3°C were detected in Cave #13 during visitation. In Cave #6, pCO_2 rose by 50 ppm but a T increase co-occurring with the pCO_2 peak was not detected. Temperature is highest at the beginning of the log, which could be due to strong influence of outside weather overwhelming the human temperature signal in Cave #6. To allow for the uncertainty related to temperature increase during human visits in Cave #6, dissolution rates were calculated for two scenarios: in Scenario 1 the cave temperature remained constant during visitation, whereas in Scenario 2 the temperature rise was similar to that observed in Cave #13. The parameters and calculated dissolution rates for the natural cave condition (0 visitors) and the cave condition during visitation (2 visitors) are shown in Table 1 for both caves. Note that it is likely that condensation corrosion occurs only when people visit the cave. Thus the dissolution rates were expressed as mm/hour because dissolution caused by visitation will not be a constant process over long time frames. Mona Island does not have large tourist numbers due to the island's visitation policy. Realistically for present island visitation a group of 30 visitors might enter an accessible pre-Columbian chamber (*e.g.* Cave #13) once per week causing a cave environmental anomaly for about 3 hours. Thus the visitor induced condensation corrosion only occurs 3 out of 168 hours or 2% of the time in accessible chambers. Table 1 shows the estimated dissolution rate due to visitation $R_{Visitation}$ in mm/year.

For both caves, dissolution rates were calculated for two visitors based on the monitoring results (Table 1), which were also extrapolated to estimate the possible effect of large visitor groups. Respiratory CO_2 emission values are directly proportional to the number of visitors (Fernández *et al.,* 1986; Faimon *et al.,* 2006). Cave temperatures rise during human visits because human body temperature is several degrees above cave temperature, and heat is radiated into the surrounding air. For relatively small temperature ranges the heat capacity of a system is constant and the temperature change is proportional to the heat source (number of visitors). The results of the dissolution rate calculation for visitor groups up to 30 people are plotted in Figure 4.

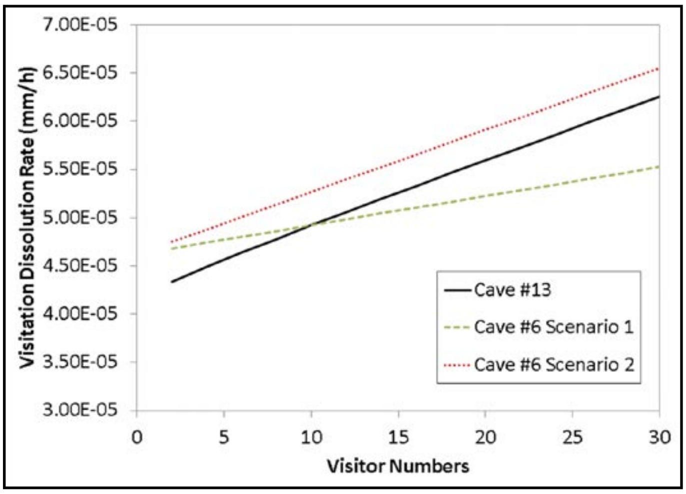

Figure 4: *Theoretical carbonate dissolution rate as a function of visitor numbers. The change in cave atmosphere has been measured for two visitors in each cave and was extrapolated for larger visitor groups. See text for details.*

Under natural conditions (0 visitors) the carbonate dissolution rates due to condensation of water along cave walls are approximately 4.20x10^{-5} mm*h^{-1} for Cave #13 and 4.62x10^{-5} mm*h^{-1} for Cave #6. Natural conditions for condensation corrosion occur only near the cave entrances, and conditions for condensation corrosion probably only occur in cave chambers during times of cave visitation. In Cave #13, a group of 30 visitors would increase the carbonate dissolution rate to about 6.25x10^{-5} mm*h^{-1} (~48%). In Cave #6, 30 visitors would increase the theoretical dissolution rate to about 5.53x10^{-5} mm*h^{-1} (~25% increase) for Scenario 1 (visitation: no temperature rise) and to 6.55x10^{-5} mm*h^{-1} (~50% increase) for Scenario 2 (visitation: temperature rise as in Cave #13).

Discussion

Cave atmospheric changes similar to those found on Mona Island have been observed in other cave settings. In Ballynamintra Cave, Ireland, two cave visitors increased the temperature by 0.3°C (Baldini *et al.,* 2006) and in Ingleborough Show Cave, UK, 30 visitors increase the cave temperature by 0.12°C in just 5 minutes (Smith *et al.,* 2013). A pCO_2 increase due to visitors has been monitored in Ingleborough Show Cave and the Grotta di Ernesto, Italy. In both caves large visitor groups raise the cave pCO_2 by up to 500 ppm (Frisia *et al.,* 2011; Smith *et al.,* 2013).

Carbonate dissolution rates on Mona Island increased due to higher T and pCO_2 levels. For 30 visitors the theoretical dissolution rates are greater in Cave #6's chamber than in Cave #13 (assuming a similar temperature rise in both caves). This is due to the higher absolute temperature in Cave #6 increasing the dissolution process via the temperature dependent kinetic constant. Both chambers have fast air exchange times (15 and 52 minutes for chambers in Cave #13 and Cave #6, respectively). In Cave #6 the monitored chamber is located between the main entrance to the west and sky lights in the cave ceiling to the east (Fig.1). Here the air exchange time is greater than in the deeper chamber in Cave #13. This result is unexpected because the close proximity to several openings should promote more vigorous cave ventilation. It seems likely that this result arises of the fast decline of the maximum pCO_2 peak in Cave #13 (Fig.3b). Probably the archaeological work took place in close proximity to the measurement site which could have formed a localized high pCO_2 air-volume causing the peak and a quick dispersal into the chamber could be responsible for the fast decline in pCO_2. Unexpectedly, the temperature declined during the work inside the chamber in Cave #6. No weather station data are currently available from Mona Island to reconstruct details of outside weather conditions during periods of cave monitoring, but in Cave #6 the outside weather seems likely to influence the cave chamber's interior. The fast air exchange time, no detectable temperature rise during visitation and the atmospheric pCO_2 values measured pre- and post-visitation indicate a close connection between outside weather and cave atmosphere that seems to overshadow visitation-induced temperature changes in Cave #6. In Scenario 1 (no temperature rise for Cave #6*)* the theoretical condensation corrosion rate for 30 visitors is smaller than in Cave #13 (Fig.4). The latter case is a result of higher pCO_2 in combination with a temperature increase in Cave #13. In Scenario 2 (similar temperature rise in Cave #6) the theoretical condensation corrosion rates are greater in Cave #6, linked primarily to the higher absolute temperatures in the cave.

Theoretical dissolution rates when a group of 30 visitors is present are up to 50% higher than compared to natural conditions. These theoretical dissolution rates represent maximum values, because they are based on an assumption that water condenses on the cave walls constantly. Condensation occurs when the cave wall is colder than the cave air (Thompson, 1978). Naturally, this occurs mostly within the first 100m of the cave, near the entrances, where external weather changes influence the cave atmosphere (Tarhule-Lips and Ford, 1998).

The presence of large visitor groups might be the only scenario in which condensation occurs in deep cave chambers. Across the island, the majority of the cave art is located in deep chambers away from cave entrances. Annual condensation corrosion rates were measured experimentally by Tarhule-Lips and Ford (1998) by monitoring the dissolution of gypsum tablets up to 100m inside a cave on Mona Island. They found mean rates of 6.7x10^{-6} mm*h^{-1}. Theoretical rates during the present study are more than one order of magnitude greater. This discrepancy between experimental results and theoretical rates is explicable for two reasons: Firstly, condensation corrosion occurs only when the conditions for condensation on the cave walls are met. Under natural conditions the diurnal temperature cycle permits periodic condensation only when the cave air is warmer. Secondly, the gypsum tablets reach thermal equilibrium after a time span of a few minutes (Dreybrodt *et al.,* 2005). Once a gypsum tablet has reached the cave air temperature no further condensation will occur on it, whereas cave walls dissipate the excess heat from condensation, and the condensation corrosion process on cave walls will persist for longer and dissolve more carbonate.

The estimated chamber air exchange times are less than one hour, and human cave air alterations fall back to natural values in one to two hours. Thus, a group visiting a cave chamber for one hour may cause condensation conditions for a total of about three hours. Considering the visitor numbers of cave systems on Mona Island, the condensation corrosion rate due to visitation has been estimated to be up to 8.3x10^{-3} mm*yr^{-1} (Table 1). Finger fluted cave art on Mona Island has a relief of less than 1mm to a maximum of c. 3mm. Thus, cave tourism over a span of decades, even of a casual and unregulated type, could pose a serious threat to cave art conservation.

Mona Island's caves are resources of outstanding natural and cultural beauty, as well as of great interest to a wide scientific community. Quite understandably they are one of the main attractions of the island. It is possible that the unique archaeology in the caves has only survived thanks to the island's remoteness, uninhabited status and the careful planning of the Puerto Rican authorities in safeguarding visitor numbers. Cave art in other well-known locations across the Caribbean has been damaged by visitors and their actions (Hayward *et al.,* 2013). Continued and future preservation depends upon institution of a conservation management plan that is sustainable in terms of resources and long-term planning, and flexible enough to allow for future access without causing a negative impact on the resources.

Perhaps, the biggest threat to the cave archaeology on Mona Island is inadvertent or deliberate contact with the cave walls (brushing past soft finger-fluting or deliberate graffiti; e.g. Fig.2e). Nevertheless, it is important to quantify threats posed by all aspects of human exposure, and also take conservation measures that will tackle sources of risk. Continued monitoring of the impact of human visitation in caves with cave art and with public access across the island, such as presented in this study, would be one way of quantifying cave microclimate alterations during visitation. Additional corrosion experiments in frequently visited cave chambers may verify the accuracy of the condensation corrosion rates estimated here are. Furthermore the provision of public information and raising awareness by studies such as these provide the best way of developing a comprehensive conservation management plan.

Conclusion

Observations of human-induced changes to cave microclimate on Mona Island showed that temperature and pCO_2 increase during human visits. Human impact promotes condensation corrosion, posing a serious threat to cave art conservation in the long term (decadal to centennial timescales). In the short term, Mona Island's remote location and current management regime ensures that visitor numbers remain low and are predictable, and therefore the risk of human-induced condensation corrosion is low. Changes in Mona Island's protected status could potentially pose a serious threat to this site however. In the short term higher risks are intentional or accidental damage related to imposition of graffiti or unregulated behaviour in the caves.

Monitoring the human impact upon archaeological sites will help to ensure a better understanding of risk factors and will form an integral part of a robust management plan for these vulnerable sites.

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