

# An assessment of drought on maize cropping success in ancient Maya lowlands during the last half of the first millennium CE

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## ABSTRACT

Drought arising from a shift in intertropical convergence zone in the Yucatán peninsula during the last half of the first millennium is often cited as a determining cause in the collapse of ancient Maya polities. Some Mayanists have postulated that a small change in precipitation might have been sufficient to result in catastrophic cropping failure, with attendant large decline in population. The supporting data for this conjecture are essentially very weak. In particular, paleoclimatologists could provide only qualitative drier or wetter periods. The data resolution has not been at the level of daily or monthly precipitation in ancient times. It is well known in the cropping of maize that the pattern, frequency, and quantity of precipitation, among other things, during the growing period are of paramount importance. Present quantitative assessment suggests that a decrease of the order of 40%, uniformly over a 125-day growing season, from normal precipitation may not have an adverse impact on maize cropping success. This finding presents doubts in the hypothetical climate-based cause of catastrophic decline in population during the period of 'Maya collapse'.

**Key words** | agriculture, climate, drought, Maya, population

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## INTRODUCTION

The first socially stratified inhabitation of the Yucatan peninsula (bound approximately 15° N and 21° N; 87° W and 93° W) was recorded to be in about 1100 BCE (Coe 2011). The ancient Maya civilization reached its zenith between about 250 CE and 900 CE, as attested by the enormous number of stone monuments (e.g., stelae and architectural edifices) discovered in successive major archeological field investigations undertaken since the 1930s. This age of 'stone monuments' is commonly known as the 'Classic period'. Prior to the arrival of the Spanish conquistadores in early 16th century CE, the ancient Mayan civilization was already in terminal decline (Coe 2011). This decline was marked notably by the precipitous decrease in the number of stone monuments erected after 1200 CE (Coe 2011). The present-day inhabitants of the ancient Maya land (mainly in the Yucatán peninsula of Mexico, Belize, and northern

Guatemala) might be just genetic descendants, with little or no veritable cultural practices of the long-forgotten ancient civilization. Relentless acculturation of the five centuries of neo-Spanish rule has contributed to this outcome.

Polities arose (and disappeared) throughout the Yucatan peninsula over the first millennium. It may be noted that the rise and fall were construed largely from the dating of the first and last stele erected in an identified polity. There is no logical reason to conclude that the stoppage of stele erection necessarily means the 'end of civilization'. Moreover, the abandonment of a polity is generally deduced inexactly from circumstantial evidence as there has been no known epigraphic or iconographic record found to have chronicled these 'abandonment' events.

In recent years, many Mayanists have opined that the catastrophic collapse of the Classic Maya Period after about 950

CE was likely due to multiple interlinked causes, in perhaps staggered sequences (see, for example, [Aimers 2007](#)). The apparent physical abandonment of these Maya polities during the end of the Classic period is commonly termed as the ‘Maya collapse’, even though the decline was occurring over the course of several hundred years. Because the conquistadores had found many ancient cities to be devoid of inhabitants after first contact in the early 16th century CE, it was reasoned that the population had crashed from thousands and even millions to virtually zero. Nevertheless, ‘Maya collapse’ is a highly popular subject of research interest among archaeologists, climatologists, ecologists, etc., presently. The various hypotheses of ‘Maya collapse’ proposed include:

- episodic prolonged droughts (see, for example, [Hodell et al. 1995](#); [Haug et al. 2003](#); [Peterson & Haug 2005](#); [Gill et al. 2007](#));
- extreme deforestation (see, for example, [Oglesby et al. 2010](#));
- decreased water supply for potable uses (see, for example, [Lucero 2002](#));
- endemic wars (see, for example, [Webster 2000](#)).

In the drought hypothesis, a significantly drier climate of the Yucatan peninsula between 800 and 1000 CE had been noted to be coincident with the construed time period of ‘collapse’ of the Classic Maya culture ([Medina-Elizalde & Rohling 2012](#)). The orthodox inference is that episodic droughts had caused subsequent reduced food supply (from cropping) to result in population collapse in many Maya polities ([Santley et al. 1986](#); [Turner & Sabloff 2012](#)). These recurring drought events do not however directly explain the apparent massive collapse of the ancient population.

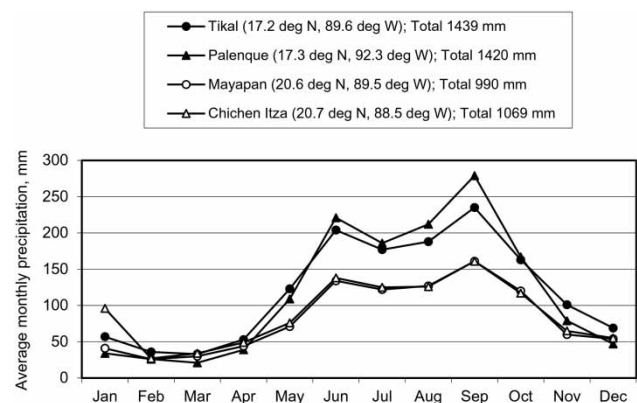
Cropping for sustenance is an important activity of the ancient Maya. Famine arising from one or more successive catastrophic crop failures (by whatever reason) might have caused the remaining population to migrate away from the affected region. There is however little or no evidence of any large-scale migration. It may be noted that the ways and means of mass migration (from the southern lowlands) would have been fraught with considerable difficulties in traversing through narrow forest trails without the aid of draft animals and wheeled vehicles.

In some contemporary literature on ancient Maya, climate change is often cited to be the driving and

deterministic force in the drastic population decline. [Normark \(2009\)](#) pointed out that many of these analyses were tainted by current popularity of climate-change discourse. Similarly, [Tainter \(2008\)](#) was particularly critical of the collapse phenomena advanced by many Mayanists to be grossly deficient in objectivity and to be heavily influenced by contemporary issues. Indeed, in many cases, findings were often sensationalized and exaggerated by extrapolation from scant facts ([Normark 2009](#)).

[Figure 1](#) shows the modern-day precipitation of Tikal and Palenque (representing southern Maya lowland sites) to be significantly lower than that of Mayapan and Chichén Itzá (representing northern Maya lowland sites). Interestingly, the southern lowlands were actually ‘wetter’ than the northern lowlands. And yet the rise and fall of example northern-lowland polities such as Mayapan and Chichén Itzá had occurred at much later dates than example southern-lowland polities such as Tikal and Palenque ([Coe 2011](#)).

Why would any migration proceed, if at all, from a ‘wetter’ region to a ‘drier’ region? No explanation has yet been offered by Mayanist paleoclimatologists on the emergence and existence of these significant Maya polities in the northern lowlands after the apparent collapse of Maya polities in the southern lowlands, before the arrival of the conquistadores. Interestingly, [Hoggarth et al. \(2016\)](#) have pointed out, somewhat incongruently, that the three major intervals of drought identified between 820 CE and 1100 CE



**Figure 1** | Modern-day (22-year moving average, i.e., 1995–2017, interpolated for a specified geo-coordinate) monthly precipitation of four ancient Maya sites. Source: [ASDC \(2017\)](#).

were concurrent with the period of political dominance of Chichén Itzá in the northern lowlands.

The objective of the present study was to analyze how cropping might be affected by the construed severe drought events in the southern Maya lowlands during the Classic period. Tikal (17.22°N, 89.62°W) was chosen as the study example. It is recognized that different geographic locations have different impacts of drought events. Generalization of Tikal specific findings to other ancient Maya sites was thus studiously avoided.

## METHODS

Literature data were used to reconstruct the impact on shortage of water (precipitation) for maize agriculture. The base line of month-by-month precipitation was derived from [ASDC \(2017\)](#) data interpolated for the specified geo-coordinates.

Maize (*Zea mays*) is generally recognized to be a widely used staple in ancient Maya. Only dryland farming of maize was assessed. It may be noted that there are (were) no permanent large rivers near Tikal. Irrigation was not deemed to be possible, as there was no means to convey irrigation water from a lower elevation (river or stream) to a higher elevation (cropped field). Generally recognized methodologies of the Food and Agriculture Organization of the United Nations ([Allen et al. 2006](#); [FAO 2016](#)) were used to estimate the water demand of maize cropping in the Tikal region.

## RESULTS AND DISCUSSION

In dryland farming, the pattern and quantity of rainfall are well recognized to have a profound effect on the success of crop agriculture. However, the total amount of rainfall during a particular period is not a good indicator of success or failure of cropping. For example, if rainfall was delayed for several weeks, it would have reduced the successful germination of the planted seeds. Similarly, if rainfall was excessively intense during a short period of time, the growing crop may have been waterlogged. In both examples,

the total amount of rainfall could be the same over the crop-growing months.

## Reconstructed climate conditions during the Classic period

Many research reports have provided proxy evidence that the Maya region had experienced a drier climate, i.e., less than average precipitation, in the distant past (see, for example, [Gill et al. 2007](#)). These drought periods were then routinely matched to presently known period(s) of decline of Maya polities, especially during the Terminal Classic period. Without any corroborating proof, prolonged drought (arising from climate change) in the Maya lowlands was subsequently inferred to have caused famine resulting in the collapse of civilization. The severity and persistence in lower rainfall in the Yucatan peninsula has generally been attributed qualitatively to the shift in the intertropical convergence zone (ITCZ; additional description is given in <http://www.srh.noaa.gov/jetstream/tropics/itcz.html>) in the northern Caribbean Sea. But there has been little or no definition of the degree of drought, e.g., detailed record of monthly record over several years.

[Medina-Elizalde & Rohling \(2012\)](#) concluded that ‘... the droughts occurring during the disintegration of the Maya civilization represented up to a 40% reduction in annual precipitation...’. It is unclear as to how a ‘40% reduction’ might be considered by these researchers to be a ‘modest reduction’. In comparison, [Carrillo-Bastos et al. \(2013\)](#) had cited a 18% reduction in precipitation in northwestern Yucatan peninsula during the ‘Maya collapse’ between 800 and 860 CE. Interestingly, Mayanists have routinely omitted any commentaries on periods (e.g., over the same span from 800 CE to 1000 CE) in which the climate was substantially ‘wetter than normal’. Using the same argumentative reasoning, the growing crop could have been waterlogged to result also in a catastrophic crop failure, which in turn, resulted in a ‘Maya collapse’. In particular, excess rainfall (soil wetness), especially during the establishment and vegetative growth stages, would have been very detrimental to the growth and yield of the maize crop (see, for example, [Mukhtar et al. 1990](#); [Zubairi et al. 2012](#)). Moreover, even a small delay in the first rainfall could have an appreciable adverse effect on final maize yield (see, for example, [Bana](#)

*et al.* 2013). The actual precipitation pattern in ancient Maya during the Classic period is unknown.

Two contemporary proxy methods used for reconstructing paleoclimate scenarios in ancient Maya are stable O<sub>2</sub> isotopes of stalagmite specimens (Medina-Elizalde *et al.* 2010) and population density of fossil pollen (Carrillo-Bastos *et al.* 2013). Unfortunately, virtually all findings published to date have been largely qualitative, i.e., being wetter or drier than normal. Indeed, many of the large-scale hydroclimatic/moisture changes are still largely tentative qualitative interpretations of paleogeological evidence (Jones & Mann 2004). The temporal resolution of geologic core sediment is low at the decadal level. In paleosciences,  $\delta^{18}\text{O}$  is a measure of the ratio of stable <sup>18</sup>O and <sup>16</sup>O isotopes. It is commonly used as a proxy measure of paleo-temperature. Details of the geochemistry of stable oxygen isotopes may be found in <https://wwwrcamnl.wr.usgs.gov/isoig/res/funda.html>. And the *quantitative* correlation between  $\delta^{18}\text{O}$  and actual precipitation is very poor. For example, the coefficient of determination ( $r^2$ ) between  $\delta^{18}\text{O}$  of stalagmite specimen to precipitation as given by Medina-Elizalde *et al.* (2010: Figure 4) was only  $\sim 0.39$ . The calibration was based on stalagmite specimen collected from Tecoh cave in 2004 and the instrumental precipitation record of Mérida (about 30 km northwest of Tecoh cave) for the period of 1966 to 1994. Nevertheless, according to Medina-Elizalde *et al.* (2010), the mean annual precipitation re-constructed for 750 CE to 950 CE might have been reduced by 36 to 52% from ‘normal’ for the region of Tecoh cave (20.73° N, 89.47° W) in northwestern Yucatan peninsula. Extrapolation of this finding to meteorological events in southern Maya lowlands is highly tenuous. After all, the Tecoh cave is located more than 700 km northwest of ancient Tikal. The reliability of quantitative reconstruction of precipitation made by Carrillo-Bastos *et al.* (2013: Figures 5 and 6) in ancient times is also somewhat wanting because of the absence of any independent verification.

Because a lack of certain critical data such as available water holding capacity of the soil and evapotranspiration, it was not possible to calculate the commonly used Palmer Drought Severity Index (Palmer 1965), a widely used means to quantify intensity, starting and ending times of drought, of ancient Maya during the late Classic period for comparison against modern-day climatic condition in maize cropping zones.

## Water demand for maize cropping

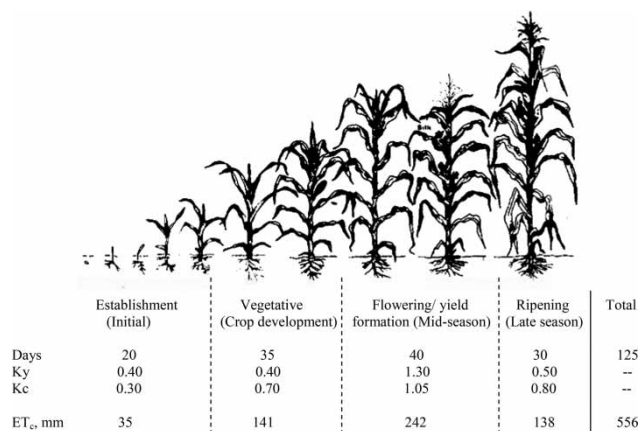
In order to put this speculation of severe drought events in ancient Maya into perspective, several scenarios of decreased precipitation on maize cropping were constructed in this study. Published FAO (2016) data on water requirement for maize cropping (adjusted for the lower hot humid tropical latitude) were used. In practice, decreased precipitation is not necessarily detrimental immediately. Moreover, during the often-described decadal drought event, there would have been ample time for ancient Maya to shift from maize to very low-water demanding staples such as cassava (Grace 1977; El-Sharkawy & Cock 1987). Cassava or manioc (*Manihot esculenta*) has been noted to be a native or introduced food plant in the Yucatan peninsula in ancient times (Colunga-GarcíaMarín & Zizumbo-Villareal 2004). Manioc is well known to have been used in the diet of ancient Maya (see, for example, Bronson 1966).

In practice, the amount and timing of precipitation relative to the growth stages are two of the critical water-supply factors affecting ultimate maize crop yield (see, for example, Hsiao & Fereres 2012: pp. 114–120). It may be noted that maize is relatively tolerant to water deficits during the crop development (vegetative) and late season (ripening) stages (FAO 2016). Excess or deficient precipitation during the other ‘no crop’ months would probably not be crucial for maize production.

Figure 2 shows an example calculation of water requirement during a 125-day maize crop in Tikal (17.2° N, 89.6° W). The methods recommended by Allen *et al.* (2006) and FAO (2016) were used. It is assumed that other cultural factors, such as the availability of macro- and micro-nutrients and the absence of pests and plant diseases, were satisfactory during all stages of plant growth in ancient Tikal agriculture.

In the calculation of the possible minimum amount of water required for maize growth, the key factors include the following:

1. Reference crop evapotranspiration,  $ET_o$  (in mm per day). In the absence of any measured data on the exact climatic and soil conditions at any location in ancient Maya, the Blaney–Criddle method of estimation was used as the best practical approach (FAO 2016),



**Figure 2** | Example crop coefficient, yield response factor, and minimum rain water demand at different growth stages of 125-day maize. Source: adapted from FAO 2016.

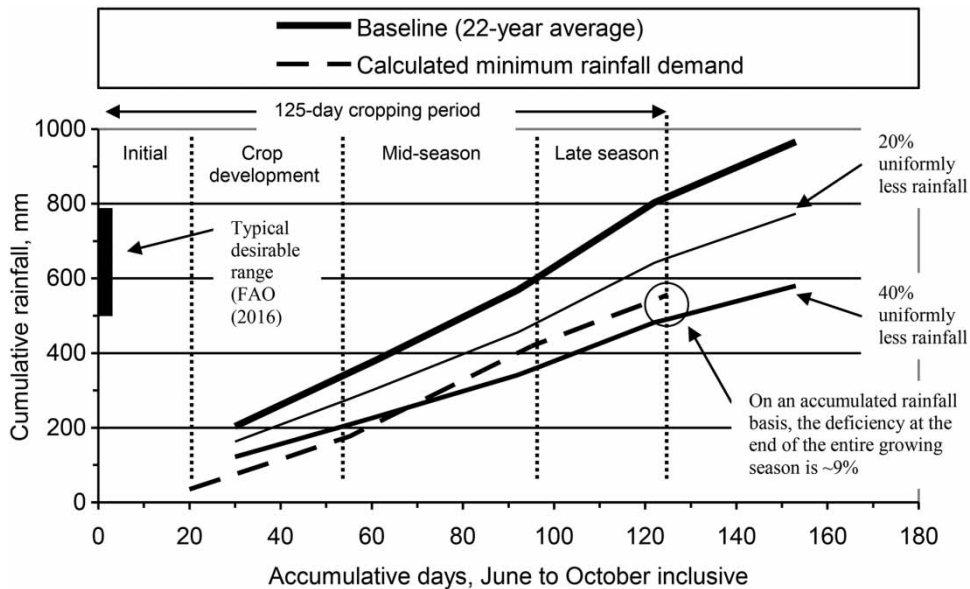
i.e.,  $ET_o = p(0.46 * T_{mean} + 8)$ , where  $p$  = mean daily percent of annual daytime hours (calculated as [daily daylight hour/annual daylight hours]  $\times$  100), at the defined latitude and  $T_{mean}$  = mean daily temperature, °C. For Tikal at 17° N.,  $ET_o$  was calculated to be 5.76 mm per day, at the estimated mean temperature for June to September, inclusive = 25.8 °C.

- Yield response factor,  $K_y$ , is normally determined experimentally. In general, crop response to water deficit (Smith & Steduto 2012) is rated as follows:
  - $K_y > 1$ , very sensitive to water deficit
  - $K_y < 1$ , more tolerant to water deficit
  - $K_y = 1$ , directly proportional to reduced water supply.
- Crop coefficient,  $K_c$ , is usually determined experimentally for a specific crop. This coefficient incorporates crop characteristics and average effects of evaporation of water from soil (Smith & Steduto 2012). The FAO data (2016) provide a range of  $K_c$  values. For the purpose of illustration, minimum  $K_c$  values at different stages of plant growth were selected for the calculation of minimum precipitation required. It may be noted that a dual-crop coefficient may be different from that of a single crop coefficient (see, for example, Shahrokhnia & Sepaskhah 2013). In ancient Maya, it is believed that three-sister cropping (Landon 2008), i.e., co-cropping of maize, beans, and chayote) may have been practiced.
- Crop evapotranspiration,  $ET_c$ , is calculated as  $K_c * ET_o$ .

## Impact of reduced precipitation

In Figure 3, the ‘20% uniformly less rainfall’ depicts the contention of Carrillo-Bastos *et al.* (2013) and the ‘40% uniformly less rainfall’ represents the conjecture of Medina-Elizade & Rohling (2012). For illustrative purposes, the decrease in precipitation was set to be *uniform* through the 125-day growing season. In this scenario, the ‘18% reduction in precipitation’ cited by Carrillo-Bastos *et al.* (2013) should probably have little or no effect on the essential water demand of the growing maize crop. Interestingly, Carrillo-Bastos *et al.* (2013: Figure 5) estimated the average annual precipitation between 50 BCE and 500 CE to be 748 mm, and between 500 CE and 1770 CE to be 898 mm. Both values would have been well within the satisfactory range of 500 to 800 mm precipitation required for maize cropping, as cited by FAO (2016). Moreover, these researchers had used fossilized pollen specimen from core sediment taken at the Ría Lagartos biosphere reserve (21.57° N, 88.09° W; about 15 km from the sea coast). The closest major ancient Maya site is Chichén Itzá (20.68° N, 88.50° W) which is located about 100 km inland southeast of the Ría Lagartos study site. It is may be noted that no proof of the validity of this extrapolation was offered by these researchers (cf. the previously described problematic issue of extrapolating Tecoh cave results to meteorological situation in the southern Maya lowlands).

In the ‘40% less rainfall scenario’ as suggested by Medina-Elizade & Rohling (2012), the precipitation shortfall would have been about 9% less (or ~65 mm in cumulative rainfall at the end of the growing season) than the calculated minimum water demand. This deficit may or may not result in a catastrophic maize crop failure. This shortfall would have been within the limit of precision of the present method calculation. The impact of any reduced crop yield on the dependent population is unknown as the baseline yield in ancient times is indeterminate. It is certainly inappropriate and invalid to project modern-day crop yield to the situation of about 1,500 years ago. Agricultural practices could be reasonably expected to be very different. There does not appear any other evidence to support the claim of Medina-Elizade & Rohling (2012) that the drier climate had



**Figure 3** | Two low-precipitation scenarios at ancient Tikal during the drier periods of the last half of the first millennium CE. Baseline precipitation was tabulated from 22-year monthly average data (interpolated for Tikal: 17.2° N, 89.6° W) published by ADSC (2017) (heavy solid line). For the present illustration, less precipitation at two levels, i.e., 20 and 40%, was set arbitrarily as a fraction of the baseline rainfall, to have occurred uniformly throughout the 125-day growing season (June to October). Minimum water demand was calculated from the Blaney–Criddle method and using  $K_c$  values (Allen *et al.* 2006; FAO 2016). ‘Calculated minimum rainfall demand’ refers to cumulative  $ET_c$  calculated on the basis of fixed  $ET_o$  and lowest  $K_c$  values (dashed line).

manifested the ‘Maya collapse’ in the last half of the first millennium CE.

At least in modern agricultural practices, there are other ways such as mulching, tillage, fertilization, crop rotation, etc., to mitigate the shortage of water in dryland farming (see, for example, Bana *et al.* 2013). There is no information of the exact method(s) of maize farming used in ancient Maya.

Additionally, in simulation of changes in air temperatures and precipitation in seven selected sites in Mexico, Conde *et al.* (1997: Figures 4 and 5) found in some cases (e.g., Coatepec and Tuxpan in Veracruz state), maize yield was increased by 10 to 30%, with a simulated 20% decrease in precipitation at a fixed temperature. Their finding highlights the pitfall in simple projection of the impact of ‘drought’ on maize crop yield, even without any consideration of linking to the ‘Maya collapse’. Similarly, reliance on the generalized drought effects on maize cropping reported recently by Daryanto *et al.* (2016) should be viewed very cautiously. These researchers based their meta-analysis on published modern agricultural practices. Such practices would not have been available in ancient Maya.

### Limitations of the present study

The actual rainfall pattern (annual or decadal) could be expected to be different in another chosen location elsewhere in the region of ancient Maya. Indeed, many other precipitation patterns (e.g., variable daily distribution) could certainly be tested numerically to assess its effect on maize crop production. Unfortunately, there are no reliable data to construct a veritable month-by-month precipitation record for ancient Maya times.

Separately, there are several critical plant-related factors which could influence the outcome of severe water deficit in any crop year. The specific phenotypes of maize planted in ancient Tikal (or any other ancient Maya sites) are unknown. The particular yield response factor as well as crop coefficient may be different from those used in the present example calculations. Moreover, the actual water retention properties of specific indigenous soil in ancient Maya would also be an important factor in the assessment of the actual impact of decreased annual precipitation on maize cropping.

It may be noted that higher air temperature frequently occurs with decreased rainfall. The calculated base evapotranspiration ( $ET_o$ ) value could be increased. For example,

a 1 °C increase in average daily temperature would have resulted in a 2% increase in the  $ET_o$  value. The resulting calculated crop evapotranspiration ( $ET_c$ ) value would be about 6 mm higher for the 40-day period of the mid-season of flowering and yield formation. This interlinked effect of air temperature was not assessed in the present study.

## CONCLUDING REMARKS

There appears no verifiable basis for the claim that drier climate had manifested the ‘Maya collapse’ during the last half of the first millennium CE. The scientific findings of paleoclimate re-construction are not in dispute presently. What is questionable is the causal link between drought arising from climate change and the cited collapse of Classic Maya. Temporal coincidence of periods of drier climate and ‘Maya collapse’ is insufficient proof of actuality. One of the problematic issues lies in missing factual data which include monthly (or even daily) pattern of changed precipitation during the period of ‘Maya collapse’ and the specific plant (and soil) characteristics of maize grown in ancient Maya. At present, the temporal resolution of changes in precipitation using any proxy protocol is too low to afford definitive calculation of meteorological events during a cropping season. Thus only unsubstantiated conjecture can be offered presently on the correlation between catastrophic famine and societal collapse. In view of numerous physical and chemical factors affecting water–soil–plant relationship, considerable caution should be exercised by Mayanist paleoclimatologists in casual linking of drought to ‘Maya collapse’, without any independent substantive corroboration.

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