Prehispanic Maya Burnt Lime Pit-Kilns and Environmental Resource Conservation

Kenneth E. Seligson
Department of Anthropology
California State University, Dominguez Hills
kenneth.seligson@gmail.com

Although the origins of Classic Maya civilization can be traced back millennia, the popular imagination continues to focus on the transitional phase toward the end of the Classic Period colloquially known as the Maya "collapse." The main objective of this paper is to shift focus to the resilience of Classic Maya society and contribute to the growing spotlight on Prehispanic Maya environmental resource conservation practices. From agricultural terraces (Chase et al. 2011), elaborate reservoir systems (Scarborough et al. 2012), and careful agroforestry practices (Lentz et al. 2018) to burnt-lime pit-kilns (Seligson et al. 2017a), Classic Maya civilization supported massive populations in a challenging tropical forest environment for over 700 years. The development of fuel-efficient pit-kiln technology toward the end of the Classic Period suggests that the inhabitants of the Puuc region of the Northern Maya Lowlands recognized that they were dealing with population-induced environmental stresses, possibly exacerbated by natural climate change. The development and widespread use of this pit-kiln technology is an example of socio-ecological adaptability in the form of communal environmental resource management. This paper evaluates Late and Terminal Classic Period Puuc resource conservation through the lens of resilience theory and argues for the importance of adaptability and a willingness to change in response to climatic or environmental variability – a lesson that is worth heeding by contemporary society.

Keywords: Burnt Lime, Resilience, Conservation, Pyrotechnology, Collapse

The Classic Maya civilization flourished for roughly 700 years (ca. AD 250-950) and was neither uniform nor static over that time span. Although its origins can be traced back millennia, popular imagination continues to focus on a transitional phase often referred to as the Maya "collapse" toward the end of the Classic Period (Figure 1). The main objective of this paper is to shift focus to the *resilience* and longevity of Classic Maya society and contribute to the growing body of work on Prehispanic Maya environmental resource conservation practices. I address this goal by evaluating the development and use of fuel-efficient burnt lime pit-kilns in the Northern Maya Lowlands through the lens of resilience theory (Figure 2).

General Chronology of the Maya Lowlands	
Postclassic Period	ca. 950-1520 AD
Late/Terminal Classic Period	ca. 650-950 AD
Early Classic Period	ca. 250-650 AD
Terminal Preclassic Period	ca. 100 BC - 250 AD
Late Preclassic Period	ca. 400-100 BC
Middle Preclassic Period	ca. 1000-400 BC

Figure 1. A general chronology for the Maya Lowlands.

Archaeologists have long recognized the Maya area as a mosaic of subregional cultural and socio-ecological variation. Examples of Prehispanic Maya environmental resource management practices abound in the scholarly corpus, and the number of such cases has only grown since the start of the LiDAR era. In the public imagination, however, the Prehispanic Maya are still seen as a homogeneous society that likely broke down or "collapsed" due to mismanagement of their environmental resources. Consideration of the potential effects that climate change may have had on Classic Maya society have entered the public mind of late due to concern for the uncomfortable parallels with the present, but the idea that this pre-modern civilization succumbed to the deleterious effects of its own practices (and ignorance) continues to have public appeal. Thus, while a more nuanced view exists within the Mayanist community, a misunderstanding of Maya conservation practices persists in non-academic circles to the disservice not only of the Prehispanic Maya, but also to their descendants living in eastern Mesoamerica today.

Fortunately, it appears that the public's understanding of the Classic Maya is trending in the direction of greater nuance thanks to increasing public outreach efforts by Mayanists. One of the more useful ways that archaeologists can continue to shift the focus of public fascination away from the idea of "collapse" is by sharing specific smaller-scale examples of pre-modern socio-ecological resilience (Smith and Mohanty 2018:1326). After explaining the importance of shifting focus to resilience from "collapse," I discuss several lines of archaeological research that have illuminated Classic Maya sustainable ecological practices and resilience. This broader survey sets the stage for a more detailed examination of how burnt lime pit-kilns represent another clear example of Maya resource conservation. I present evidence from a case study of lime production at the mid-sized urban center of Kiuic in the Puuc Region of the Northern Lowlands. The earliest settlement at the site dates back to at least 800 B.C. (Gallareta Negron et al. 2014), but like many other sites in the Puuc, Kiuic's population and architectural program expanded dramatically during the Late and Terminal Classic Periods. Elite compounds such as *Escalera al Cielo* that included a high frequency of vaulted architecture were constructed on hilltops surrounding the site center. This growth may have strained natural resources. Previous archaeological work has

Figure 2. A map of the Maya Lowlands, highlighting the location of Kiuic (adapted from Seligson et al. 2017a).

suggested that the production of burnt lime contributed to environmental degradation. In this paper, I argue that the development of fuel-efficient burnt lime production technology at Kiuic and in the Puuc Region more broadly is an example of communal environmental resource management (see image facing title for burnt lime production episode using pit-kiln).

Shifting the Focus from "Collapse" to Resilience

In order to appreciate the importance of shifting the focus to Classic Maya conservation practices, we must first explore the appeal of studying societal disruption. Fascination with the breakdown or "collapse" of complex societies likely emerged soon after the earliest complex societies broke down. When used in reference to sociopolitical systems, the term 'collapse' connotes a degree of suddenness that cultivates curiosity but is often inappropriate for the given set of circumstances (Diamond 2005; McAnany and Yoffee 2010; Middleton 2012; Tainter 1988, 2006). Although there are indeed several examples of rapid sociopolitical fragmentation or transformation in the past, more often, societal breakdowns are more accurately understood as gradual declines. Individuals living through what we might now view as a period of rapid dissolution may never have conceived of their lifetimes as having encompassed such calamitous downward trends. Thus, timescale is an important dimension that must be considered in any discussion of collapse, especially when the focus is on human-environment relationships. It is also important to consider issues of geographic and population scale, as local community-level sociopolitical trends may differ from those of sub-regions or broader cultural areas.

One of the factors likely contributing to our contemporary fascination with ancient societal breakdowns attributed to socio-ecological causes is the superficially comforting idea that we are (or can be) better at managing our resources today (Middleton 2012). We believe that with our molecular-level scientific understanding of nature and advanced technology, we can avoid ecological calamities or fend off climatic disasters that doomed societies past. Even with the blaring warning signs all around us, some of us take comfort in our *potential* to save ourselves. A related notion is that even if we accept the impermanence of our own society, surely our demise will not be as "catastrophic" as societies past. We can look to the past for examples of societal breakdown that will allow us to take solace in our relative success. A final related line of thinking posits that our fascination with smoking gun natural disaster explanations (earthquakes, volcanoes, drastic climatic changes, etc.) for the fall of past societies may stem from a desire to exculpate human agency from societal breakdowns. Thus, almost to hedge our bets, we think that if we cannot or *choose not* to act, it does not matter because "nature" would win in the end anyway.

Although societal stability may not be as attention grabbing as societal collapse, if we can instill an appreciation for the broad time-scale of Classic Maya civilization, it should be awe-inspiring how long such a complex set of interlocking structures was able to survive. For instance, 700 years ago, Europe was reeling from the black plague, the khanates of the Mongol Empire were thriving, and the first *tlatoani* of the Mexica was about to be consecrated. Whether one uses the end of World War II or the Cold War as the benchmark, our current global order is well shy of 100 years old.

One of the factors contributing to the longevity of the Classic Maya system was socio-ecological adaptive capacity, a point to which I will return in the following section. Complex societies are often composed of several sociopolitical factions and socioeconomic groups that differ in access to wealth, power, and decision-making opportunities (Hornborg 2005). Archaeologists investigate the material record for evidence of compromises between factions (cooperation and/or collective action), imposition of one group's interests on the society as a whole, or a mixture of the two. Oftentimes it is very difficult to distinguish one set of circumstances from another. In strictly hierarchical societies, powerful factions could make decisions relating to human-environmental relations that reflected their own interests at the expense of the community at large (Demeritt 2005; Middleton 2012; Tainter 2006). Compromises between competing factions may lead to short-term solutions that over time lower risk thresholds and weaken the potential resilience of societies faced with sharp environmental or external crises (Butzer 2012). This situation is unfortunately visible today in the hesitancy of contemporary governments to change energy policies in the face of human-induced climate change.

In recent decades, the combination of increased environmental consciousness and decolonization efforts in academia have led to a shift in archaeological studies of socio-ecological relationships toward a focus on sustainability instead of environmental overexploitation and mismanagement (Ford and Nigh 2009; Lentz et al. 2018; McAnany and Yoffee 2010; Scarborough et al. 2012). However, while there are a handful of examples (Erickson 1988; Morrison 2015), we as archaeologists are often unable to take methods and/or technologies from the archaeological record and directly apply them to the modern day. Archaeological studies do however help us better understand the past and recognize what aspects of sociopolitical and ecological systems are adaptable or changeable in order to improve modern policies and practices, rather than conceptualizing current systems as so ingrained that they have immutable 'built-in' impediments (Redman 2005; Redman et al. 2009). Archaeological investigations of sub-regional scale responses to changing human-environment circumstances and their outcomes, such as this current study, contribute to the growing body of data emphasizing the importance of adaptability. Lessons from sunk cost analyses of past societies indicate that no matter how difficult, societies need to find ways to change the underlying principles of socio-ecological relations before they exhaust options for course correction (Fisher and Feinman 2005:65; Janssen et al. 2003). Instead of sating the contemporary public's appetite for cross-temporal schadenfreude, we should focus instead on promoting the socio-ecological resilience of the Classic Maya.

Classic Maya Conservation Research

A brief overview of three broad areas of Maya conservation research demonstrates that socio-ecological resilience and proactivity were prominent aspects of Classic Maya societies. The first aspect of the Maya environmental resource conservation concerns agricultural adaptations. Maya communities took several steps to manage their agricultural resources, including using a wide array of terracing methods (Beach et al. 2002:391; Beach et al. 2015; Dunning and Beach 1994) and supplementing milpa fields with house gardens (Ford and Nigh 2009; Lentz et al. 2018). Terracing hillslopes not only increases the scale of food production, but also limits negative effects such as soil erosion and loss of soil nutrients. Terraces represent Maya adaptation to feed growing populations and sustain resources over the course of the Classic Period (Battistel et

Figure 3. Photo of a partially collapsed vault at the site of Kiuic showing the amount of lime mortar that would have been necessary to construct these buildings (photo by author).

al. 2018; Beach 1998; Dunning and Beach 1994). Scholars have begun to abandon early models of a slash-and-burn agriculture (Anderson et al. 2012), and terrace systems dating in some cases as far back as the Preclassic Period have been identified across the Maya lowlands (Arnauld et al. 2013; Beach et al. 2002; Brennan et al. 2013; Dunning et al. 2012; Canuto et al. 2018; Chase et al. 2011; Garrison et al. 2019; Golden et al. 2016; Lamoureux-St-Hilaire et al. 2015; Inomata et al. 2018:32; Neff 2012; Robin 2015; Turner and Sabloff 2012).

Likewise, studies of water management in the Lowlands have demonstrated that the Maya engineered intricate systems to capture and store water. Household-level management systems (Brewer 2018; Chase 2016) were supplemented by larger more elaborate polity-wide projects that likely had some degree of central organization and could better withstand fluctuations in annual rainfall (Ertsen and Wouters 2018). Individual household cisterns, large reservoirs, irrigation systems, and wetland agriculture have all been identified across the lowlands (Brennan et al. 2013; Brewer et al. 2017, 2018; Fedick et al. 2000; Ferrand et al. 2012; Glover 2012; Golden et al. 2016:305; Isendahl 2011; Lucero 2002; Luzzadder-Beach et al. 2016; McAnany 1990; Scarborough et al. 2012; Thompson 1897; Zralka and Kaszkul 2015).

A third component of the Prehispanic Maya conservation program, directly related to lime production, was forest management. Increasingly nuanced understandings of the roles that the Prehispanic Maya played in shaping their tropical forest homes are leading to a greater appreciation for the productivity and ecological balance they were able to maintain. Paleoenvironmental reconstructions demonstrate that from the time of the earliest settled villages in the Lowlands, the Maya carefully began to modify the natural environment into sustainable "forest gardens" (Ford and Nigh 2009). The Classic Maya anthropogenic ecosystem demonstrably supported large populations by employing not only the agricultural and water management practices mentioned above, but also a mixture of fallow swidden cycles and sophisticated arboricultural practices (Gomez-Pompa 1987; Lentz et al. 2014, 2016, 2018; Luzzadder-Beach et al. 2016; Scarborough et al. 2012; Steinberg 2005).

Prehispanic Maya Burnt Lime Production and Socio-Ecological Resilience

Burnt Lime Production and Conservation

Burnt lime production factors into discussions of Prehispanic Maya resource conservation because of the amount of wood fuel that would have been necessary to produce massive amounts of burnt lime for construction (Figure 3), dietary, and sanitary purposes (Seligson et al. 2017a). Historical accounts of the Maya using large aboveground pyres to produce lime led to hypotheses regarding its role in deforestation as far back as the early 20th century (Hansen et al. 2002; Morris et al. 1931; Schreiner 2002). This technique includes a relatively high ratio of wood fuel to burnt lime and is known as the "traditional" method for Maya lime production due to a lack of evidence suggesting alternative Prehispanic production methods. Although the idea that lime production played a significant role in deforestation and environmental degradation throughout the Lowlands has been successfully challenged (Abrams and Rue 1988; Seligson et al. 2017a; Wernecke 2008), methods of burnt lime production and levels of consumption likely varied by region, site, and time period (Seligson et al. 2018). Regardless of whether lime production would have severely strained fuel resources in the Northern Lowlands, the identification of a distinctive fuel-efficient lime pit-kiln technology in this region suggests that Prehispanic lime producers were indeed concerned with the possibility of dwindling fuel resources.

Recent excavations in the Puuc region and Northwestern coastal plains of the Yucatan Peninsula have uncovered evidence of a Prehispanic pit-kiln technology (Figures 4, 5) that was

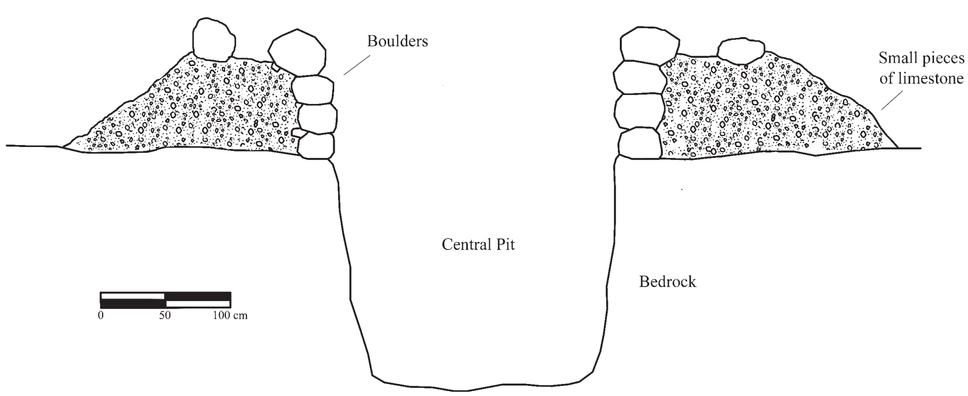

Figure 4. Schematic rendering of a profile cut view of a burnt lime pit-kiln modeled on a pit-kiln excavated at Kiuic (drawing by author).

Figure 5. Photo of a pit-kiln prior to excavation (photo by author).

likely more fuel-efficient than "traditional" aboveground pyres (Ortiz Ruiz et al. 2015; Seligson et al. 2017a. 2017b; Seligson et al. 2018). Pit-kiln use in the Puuc became increasingly common during the Late and Terminal Classic Periods (ca. 650-950 AD) when many sites in the region were experiencing population increases and architectural expansion (Gallareta Negrón et al. 2014; Seligson et al. 2017a). While aboveground pyres produce burnt lime with an average range of 5:1 to 12:1 wood fuel to burnt lime (Gallareta and May 2003; Levy and Hernandez 1995; Morris et al. 1931; Russell and Dahlin 2007; Schreiner 2002;), experimental firing of a model pit-kiln near the site of Kiuic resulted in ratio of 3.94:1 (Figure 6) (Seligson et al. 2017a). The demonstration that the pit-kiln method could provide at least a 20% increase in fuel efficiency over the "traditional" method may explain its widespread adoption in the Puuc and surrounding areas. Lime producers in the region may have recognized the potentially disastrous effects of meeting the growing demand for lime using only aboveground pyres that required significant quantities of wood, a finite resource. Pit-kilns may have been one of a number of alternative experimental techniques with the aim of conserving resources by limiting the amount of wood required to produce the burnt lime used for a variety of purposes.

Ethnographic analogy provides insight into another possible element in this conservation program. Working with local collaborators just outside the Puuc region, Dean Arnold (see Seligson et al. 2017b:573) demonstrated the extent to which contemporary limestone specialists were able to pick out specific types of stone that would maximize the efficiency of lime production. Such esoteric knowledge prevents wasting wood fuel to attempt to calcine grades of limestone that would never transform regardless of how long or hot the fire burned. This specialized understanding of limestone was likely passed down from generation to generation. Thus, detailed knowledge of raw materials would also have contributed to resource conservation.

Burnt Lime Production and Resilience Theory

Over the last several decades, resilience theory has been adapted by archaeologists to address issues of social complexity (Blanton 2010; Bradtmoller et al. 2017; Redman et al. 2009;). At its most basic, the adaptive cycle at the heart of the socio-ecological resilience model consists of four stages (growth/expansion, conservation/storage, release, and reorganization). The conservation/storage stage is characterized by a measure of stability, while the release stage refers to the breakdown or collapse of the existing system. In this model, resilience is a measure of the adaptive capacity of a given social system to survive unpredictable disruptions (Blanton 2010; Holling 2001:394; Lentz et al. 2018). Fascination with the dynamism of phase changes, mainly from an era of stability to one of disruption or chaos, draws scholars and the public alike in to try to understand the factors involved (Blanton 2010). I, instead, would like to call greater attention to the adaptive mechanisms at play *during* the conservation phase that supported Classic Maya socio-ecological resilience. Although resilience frameworks have been applied to archaeological cultures on the broadest societal scales, there have been relatively few studies applying these

Figure 6. Photo of the experimental pit-kiln soon after the burn began (photo by author).

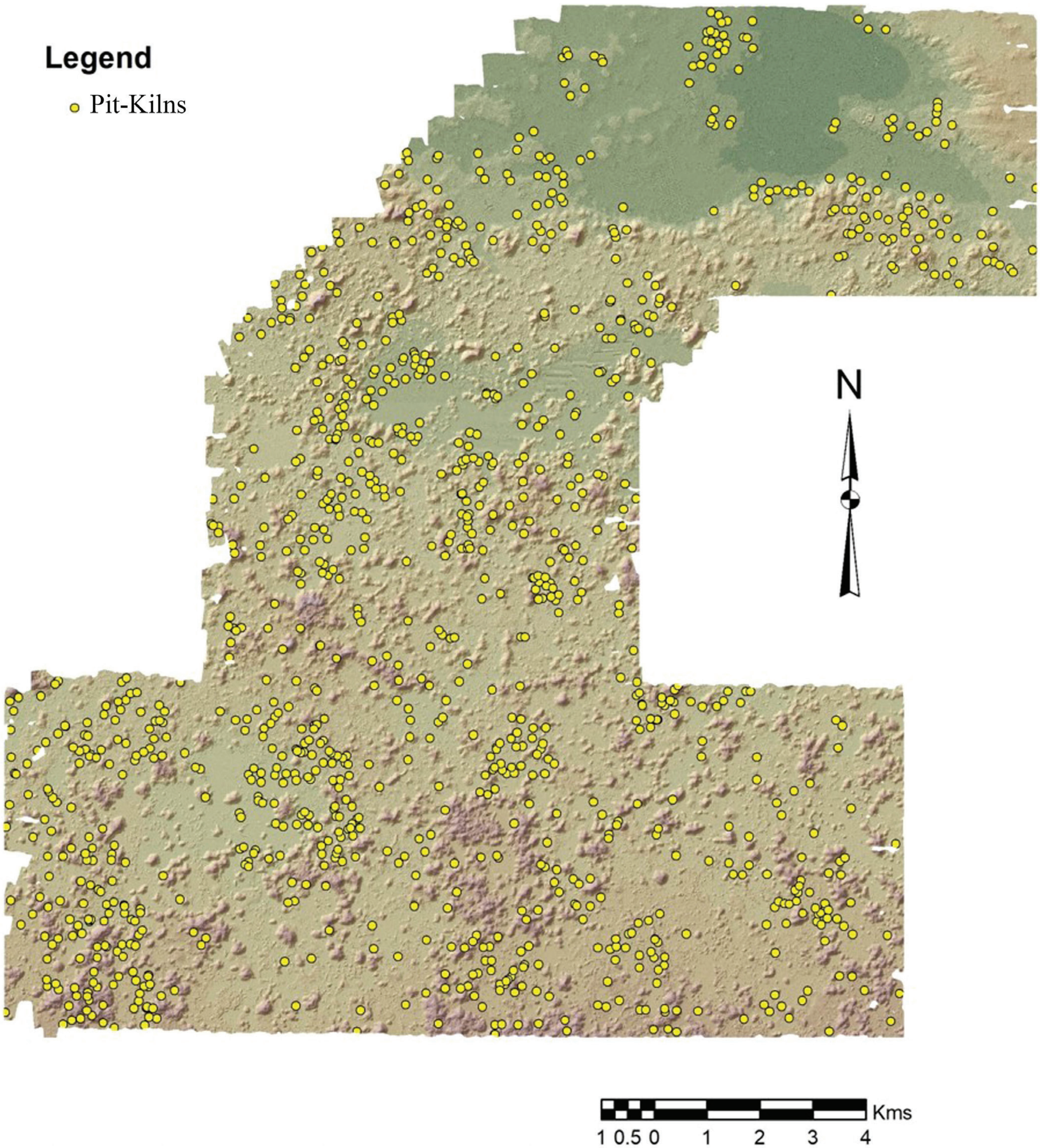

Figure 7. A map of 238-sq-km LiDAR flyover zone of the Eastern Puuc region highlighting the locations of pit-kilns (map credit: William Ringle).

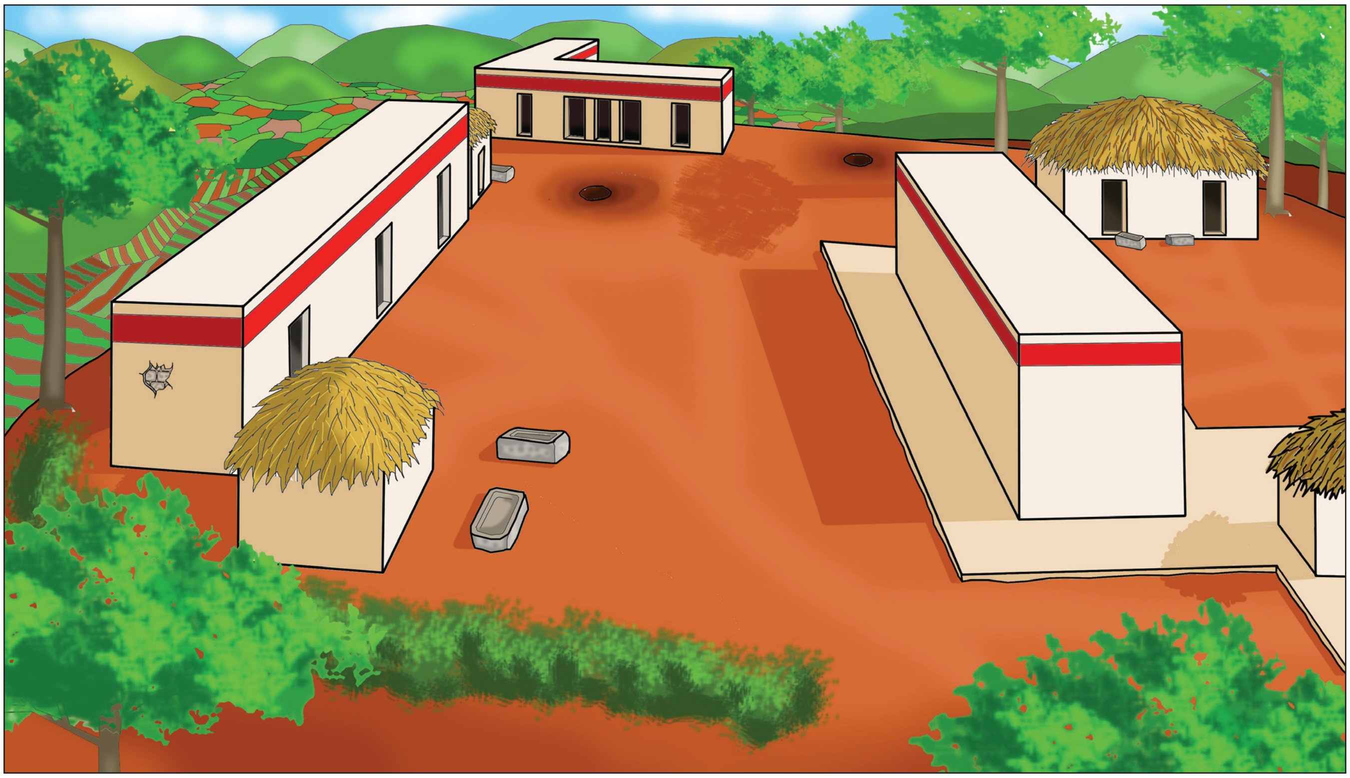

Figure 8. Artistic rendering of the hilltop complex of *Escalera al Cielo* located to the west of the Kiuic site center demonstrating the amount of architectural lime used in this residential group (drawing by author).

models at the site scale of analysis (Bradtmoller et al. 2017).

The development and widespread adoption of lime pit-kiln technology at the site of Kiuic represents an adaptive strategy on the part of the Prehispanic Maya that serves as a lesson in resilience for us today. During the Late and Terminal Classic Periods, Kiuic either transitioned very rapidly from the growth to the conservation phase of an adaptive cycle, or experienced overlapping cycle phases at different social scales. The site was experiencing population growth, which required new and innovative ways of efficiently using and conserving resources in order to maintain a functioning society. The adoption of fuel-efficient pit-kiln technologies during this time is consistent with the idea that Kiuic was experiencing the conservation phase of the adaptive cycle. A broader Lowland Maya adaptive cycle experiencing the release and reorganization phases of its cycle may have exerted external pressures on Kiuic and other Puuc sites, but inhabitants of the region took steps to absorb the shock by conserving wood resources. Significant demographic expansion in the Puuc began in the Late Classic and yet over two hundred years later the Kiuic community was still thriving enough to begin construction on new palace complexes (Gallareta Negrón et al. 2014; Ringle 2005). Additionally, the frequency of vaulted non-royal architecture increased during the Late and Terminal Classic Periods in the Puuc, indicating that communities were thriving. Communal conservation efforts exemplified by, but likely extending beyond, the adoption of the pit-kiln technology would thus appear to have been successful in helping to manage fuel availability and should be seen as a measure of the adaptive flexibility of the system. Lime production may have actually been somewhat negligible compared with some other fuel needs, such as for ceramic production, tools, construction, and furniture (Farahani et al. 2017:994; Lentz et al. 2018), but a 20% increase in fuel efficiency for any facet of fuel consumption would have contributed to long-term resilience. Additionally, it is quite possible that the more fuel-efficient pit-kilns were used to fire ceramics, though no wasters or other direct lines of production evidence were uncovered. The high levels of potassium and phosphorous identified within the excavated pit-kilns suggests that they may have served other burning function as well, such as trash disposal or fertilizer production, though future studies are needed to confirm all of these possibilities.

One final issue is that of the organizational level of the lime pit-kiln conservation program. Looking beyond Kiuic, Bill Ringle and colleagues (2018) have recently identified over 1,000 pit-kilns in a 238-km2 area of the Eastern Puuc region using data gathered from a LiDAR flyover (Figure 5). These numbers indicate that the Eastern Puuc as a whole adopted this technology, which may be viewed as an example of collective action to address environmental stress factors. Although the widespread availability of limestone suggests that it would have been accessible to almost everyone, the greater possibility for wood fuel supply exhaustion would have likely fostered the development of a community-wide mechanism to regulate usage (Carballo et al. 2014). Lentz and colleagues (2018) in their analysis of forest management practices at Tikal hypothesize that there must have been some sort of societal control to protect forest resources, and suggest that a central authority would be the most likely basis for such management.

It is unclear whether the widespread adoption of burnt lime pit-kilns was the result of communal cooperation or a top-down decree, but the community-wide benefits resulting from widespread adoption supports grassroots collective action as a viable scenario. Community members would likely have been eager to adopt a technology that limited the amount of raw materials and labor necessary for production (Figures 7, 8). Within the much smaller communities of the Eastern Puuc, such as Kiuic, it is possible that it would have been that much easier for a central authority to exert control over fuel consumption. However, it is also more likely that in a smaller, closer-knit community, moral codes and neighbor monitoring could have played just as important an incentive to join a program that benefited the broader community (Blanton 2010:43; Houston and Inomata 2009:40-41; Lichbach 1996). Future excavation of additional pit-kilns to refine chronologies regarding their construction and use may help clarify this issue.

Conclusion

Ford and Nigh (2009) have argued that instead of viewing the Classic Maya as steadily building toward socio-ecological disaster or deforestation, we should appreciate Classic resource management practices for the 700-plus year sustainability that they supported in many subregions. From agricultural terraces, elaborate reservoir systems and careful agroforestry practices to burnt-lime pit-kilns, Classic Maya civilization sustained massive populations in a challenging tropical forest environment for over 700 years. The Puuc Maya recognized that they were dealing with population-induced environmental stresses, possibly exacerbated by climatic changes. This paper is by no means arguing that the Prehispanic Maya had some type of mysterious knowledge of how to live in harmony with their natural environment that has been lost through the ages, nor that they achieved a net zero carbon balance. Instead, the purpose of this case study is to emphasize the importance of adaptability, the willingness to change in response to climatic or environmental variability.

This paper is far from the first to highlight the value to contemporary society of the examination of societal processes on an extremely long time-scale by archaeologists, but I want to close with a specific, feasible way in which our long time-scale approach can help underline the importance of socio-ecological adaptability. We must try to instill an appreciation for the long arc of human actions and effects, a mindfulness that geologist Marcia Bjornerud (2018) has recently referred to as "Timefulness." While archaeological time is not quite as deep as geological time, there is utility in carefully choosing how we discuss sociopolitical declines and what aspects of pre-modern civilizations we choose to emphasize. We must work to popularize our understandings of pre-modern societal breakdowns as the attenuated declines that they often were. The so-called Classic Maya "collapse" spanned a period of roughly 250 years – for reference, the United States is just shy of its 250th birthday.

We can point to the success of such pre-modern conservation efforts as fuel-efficient pit-kiln technology as proactive examples of long-term planning by societies that lacked modern technology. The Puuc Maya took steps to stave off societal breakdown while other areas of the lowlands were in decline, and even though their system eventually succumbed, their proactivity and recognition of the importance of taking steps to confront future crises can serve as a model for us today. Although we may not see the positive or negative effects of our actions as soon as tomorrow, this should not discourage us from taking collective action now to expand our socio-ecological adaptability in order to prevent future crises.

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