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Imperial resource management at the ancient Maya city of Tikal: A resilience model of sustainability and collapse

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ABSTRACT

Over the time span of more than a millennium, the ancient Maya polity of Tikal went through periods of growth, reorganization and adaptive cycles of various connected scales. Recent data show that following the reorganization of the Late Preclassic period, Tikal experienced an extended period of technological innovation and population growth that eventually stretched the carrying capacity of the available landscape. A hydraulic system was constructed that provided water for the community during the dry seasons: a powerful development in an area without a permanent water source. Agriculture was intensified using a combination of root crop agriculture, irrigated fields, arboriculture, household gardens, short fallow cropping systems and *bajo* margin cultivation. The net product of these diverse production activities helped to underwrite an enormous amassing of economic and political capital during the Late Classic period. Ultimately, in the mid-9th century CE, expansive growth combined with multiple system disturbances led to a collapse of the city's social structure followed by abandonment of the site. The application of resilience theory as a conceptual framework is useful in helping to interpret the complex web of the underlying social and ecological domains that contributed to Tikal's demise.

1. Introduction

The ancient city of Tikal, once a leading polity of the ancient Maya world, has drawn the attention of scholarly investigation for over a century. Despite the long history of academic research, the intricate relationship of the densely populated center with its surrounding tropical forest environment has only recently come into clear focus. How the occupants of Tikal managed their precious water supply in the face of regular seasonal droughts without access to any permanent body of water and how they provided adequate supplies of food and forest products to expanding populations during an occupation that lasted over 1500 years have been questions of ongoing debate. The sudden abandonment of the city in the mid-9th century CE, especially, has long been a topic of enthusiastic discussion among scholars. Although the data generated by the current study have drawn insight from the settlement pattern research of many previous scholars, (e.g., Puleston, 1983; Ford, 1986; Fry, 2003), the multi-disciplinary research approaches outlined in this paper are unique in that they focus on the integration of the ancient Maya of Tikal with their neotropical environment in an effort to resolve the lingering questions regarding ancient Maya land use.

Tikal is situated near the southern end of what is sometimes referred to as the Elevated Interior Region (EIR) of the Maya Lowlands (Fig. 1), a complex physiographic region that lies at the epicenter of the Yucatan Peninsula (Dunning et al., 2012). The EIR essentially is a raised ancient sea bed comprised largely of exposed strata of Lower Tertiary and Late Cretaceous carbonate rock, uplifted and modified over many millions of years. The bedrock of this karst region is highly porous and the permanent water table typically lies dozens of meters below the surface, which made groundwater essentially unavailable to the ancient Maya except through occasional deep caves or *cenotes*. The region has numerous large depressions that gradually fill with water during the rainy season. Dispersed among these depressions, or *bajos*, are undulating well-drained, upland areas (Dunning et al., 1998). The native vegetation of the depressions has a low canopy (10–20 m) comprised of trees like *palo de tinto* (*Haematoxylon campechianum* L.). The upland areas, with much taller tree species (30–40 m), are dominated by trees such as *sapodilla* (*Manilkara zapota* [L.] P. Royen) and *ramón* (*Brosimum alicastrum* Sw.). Of course, the vegetation is much more variable than this simple dichotomy would suggest owing to fine-scale variability in rainfall patterns, edaphic conditions and lithologic factors (Dunning et al., 2009). Basically there is a continuum of forest types that include true swamps in areas with permanent standing water, mesic *bajos* that are wet in the rainy season only, dry scrub swamps, mesic upland forest with its tall forest trees, and upland forests on gravelly elevated sites, locally called "*ramonals*." Between the extremes there is a transition

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Fig. 1. Map of the ancient Maya world showing the location of Tikal and other major centers mentioned in the text. The Elevated Interior Region, a raised karst landscape at the epicenter of the Yucatan Peninsula, is demarcated in gray (figure by Nicholas Dunning and Chris Carr).

forest that includes species from both upland and *bajo* forests (Schulze and Whitacre, 1999).

At a fundamental level, the diachronic study of Tikal has illuminated our knowledge of the local history of forest resource use and hydraulic agricultural adaptations that sustained the development of the polity for more than a millennium. Ironically, these same resource extraction strategies, which worked well for many centuries, may have contributed to the demise of Tikal and other major centers of the Maya lowlands, as well. On a theoretical level, this study of Tikal contributes to a refined model of environment and civic-center interaction in Maya society in particular and complex societies in general. Using empirical data relating to the agroforestry, agricultural and water management activities of the ancient Maya at Tikal, we now have a sturdy platform upon which to build a conceptual framework of land use through time and a greater understanding of how those practices were, in some ways, sustainable but in other ways, were not.

1.1. Resilience theory

The overall thrust of this paper is grounded in the theoretical precepts of resilience and panarchy theories. Initially developed in the fields of ecology (Holling, 1973) and psychology (Garmezy, 1985), resilience theory was adopted by archaeologists as a conceptual tool that enabled a more nuanced theoretical framework to address the dynamic aspects of complex adaptive systems (e.g., Gunderson, 2003; Bradtmöller et al., 2017). Based on the underlying parameters of ecosystem function, adaptive systems operate at multiple scales, including the level of the individual community. In this theoretical perspective, communities often pass through cycles consisting of four behavioral domains: growth or exploitation (r), conservation (K), release (Ω), and reorganization (α). Degrees of connectedness and potential are important aspects of each domain. Potential, in this context, refers to the number and kind of future options available. Connectedness, on the other hand, is reflective of the degree of rigidity or flexibility of the system (Holling, 2001). The "growth" or "expansion" domain, as the name implies, is represented by a time of rapid growth and colonization of unoccupied habitats or recently disturbed areas. The "conservation" domain is characterized by a slow accretion and storage of materials and energy. "Release" is a period of rapid negative change that can take the form of "collapse" where tightly controlled quantities of biomass are suddenly released, initiated oftentimes by external agents. The "reorganization" domain represents the aftermath of a societal release when resources are reorganized into a new system to exploit available opportunities (Redman, 2005). In theoretical terms, these four behavioral domains constitute a single cycle and the trajectory of spatial and temporal attributes of a system will develop across them (Bradtmöller et al., 2017).

Panarchy theory expands upon the resilience model by incorporating the concept that scales can increase as systems become more complex. In this view, economic, social, and ecological systems are vitally interconnected (Walker et al., 2004; Blanton, 2010; Nelson et al., 2010). Individual adaptive cycles can be nested in a cluster of hierarchies within space and time. Nested hierarchies tend to have a stabilizing effect because they contribute a memory of the past, despite temporal distances, and aid recovery following dramatic change. Through a collective memory, social organizations have the capacity to move socioecological systems toward a desired state, oftentimes toward systems of greater complexity. However, revolt or collapse can occur when small scale transformations become synchronized across scales and develop into a larger crisis. The causal factors that influence whether a system experiences complete collapse or recovery, and its rate of recovery, are largely dependent on three system attributes: (1) the options available for change; (2) the interconnectedness or rigidity of the system, and (3) the overall resilience of the system and its ability to withstand unexpected perturbations. Cycles of memory and revolt serve to interconnect adaptive cycles of different scales and can alter the dynamics of individual adaptive cycles. These concepts, taken together, form the theoretical framework of panarchy, an important adjunct to the resilience model (Gunderson and Holling, 2002).

1.2. Political history of Tikal

Around 700–800 BCE the first colonists of Tikal entered the Petén rain forest in what is now northern Guatemala, an area that is uniquely devoid of perennial lakes and rivers. Why these early colonists chose this site is uncertain, although the recent discovery of a freshwater spring emanating from the base of a high bluff, just north of where Temple 5 now stands, likely was an attractive feature for the founding population (Scarborough and Grazioso, 2015). The earliest monumental architecture at Tikal appeared around 600 BCE in precincts of the budding metropolis known as the North Acropolis and the Mundo Perdido complex (Laporte, 2003). By 350 BCE in the Late Preclassic period, Tikal had developed into a significant regional polity within the political framework of the Maya Lowlands, even though it was dwarfed by the larger Preclassic centers of the Mirador Basin to the northwest.

Somehow, Tikal managed to endure the political and climatic turmoil of the Late Prelassic period (350 BCE-250 CE) and survived unscathed despite the abandonment of several nearby Maya centers, e.g., El Mirador and San Bartolo. Moving into the Early Classic period, Tikal seemed to have recovered adequately (i.e., the city maintained its population base and political prestige) following the droughts of the Terminal Preclassic (Medina-Elizalde et al., 2015; Webster et al., 2007; Iannone, 2014).

By the third century CE, Tikal emerged as a major power in the

Early Classic period (Coe, 1967; Schele and Freidel, 1990; Dunning et al., 2014). The rising star of Early Classic Tikal did not go unnoticed; in 378 CE, Teotihuacan, the pre-eminent power of Mesoamerica at the time, became actively involved in the local politics of Tikal. Some scholars, based on epigraphic evidence, have proposed that Teotihuacan placed a Mexican lord on the throne of Tikal (Martin and Grube, 2008). Wright (2012) has questioned this assertion, however, based on strontium isotope analysis of royal burials at Tikal, but she did observe a significant presence of migrants in elite Early Classic tombs which supported the concept of the Maya-Mexican alliance, if not the lineage details. In any case, the alliance proved to be advantageous, at least for Tikal, and the regional influence of Tikal increased substantially during that time. Following this, the polity prospered greatly for more than a century and became a leading economic power in its own right.

Subsequently, Tikal went into a period of decline in what is commonly called the "hiatus," as indicated by a dearth of commemorative stelae and monumental construction. This political and economic downturn has been attributed to a series of major military setbacks (Martin and Grube, 2008) and the damaging effects of a nearby volcanic eruption in 536 CE (Dahlin and Chase, 2013). In the mid-6th century, Tikal was eclipsed by the Kan dynasty to the north at Dzibanche and later Calakmul. Caracol, from the southeast, also recorded military victories over Tikal during the Early Classic period which further diminished its regional hegemony during this time period (Chase and Chase, 2017).

Around 695 CE, however, Tikal came roaring back through a sequence of stunning military successes led by the eminent ruler, Jasaw Chan K'awiil and his son, Yik'in Chan K'awiil. As a result of these events, the city regained its former socio-political and economic prominence in the region (Martin, 2003) and became a key node in the trans-isthmus obsidian trade (Hammond, 2000). Tikal then entered a golden age of innovation and cultural transformation in the Late Classic period (8th and 9th century CE), during which time unparalleled developments in monumental architecture took place, including the construction of a royal palace, the Central Acropolis (Fig. 2), and six towering pyramidal-shaped temples (Fig. 3), that continue to marvel scholars of architecture and archaeology alike (Harrison, 1999; Lentz and Hockaday, 2009). The population of the city also grew dramatically during the Late Classic period, at least tripling and possibly quadrupling in size (Haviland, 1970; Culbert et al., 1990). Tikal continued its military and economic dominance in the region into the 9th century CE (Martin, 2003).

Fig. 3. Temple 1, a prominent edifice of the Great Plaza, is also known as the Temple of the Giant Jaguar. One of six major pyramidal temples at Tikal, this structure covers the tomb of Jasaw Chan K'awiil, a great lord of the Late Classic Maya (photograph by David Lentz).

By the mid-9th century, however, the threads of Tikal's cultural fabric began to unravel. Speleothem data (e.g., Medina-Elizalde et al., 2010; Kennett et al., 2012) reveal there was an extensive, multi-decadal period of extremely low rainfall in the Maya Lowlands in the middle 9th century (820–870 CE). This defined dry period strikingly coincides with the abandonment of the site core of Tikal. The dramatic drop in city population was already well underway by the time of the construction of the last dated monument, Stela 11, in 869 CE (Martin, 2003; Houston and Inomata, 2009). This was a sudden and ignoble end to a great city as it ceased to serve as a cultural, religious and economic center of the Maya realm.

Fig. 2. Photograph of the Central Acropolis, one of the foremost palaces of the Late Classic Maya at Tikal (photograph by David Lentz).

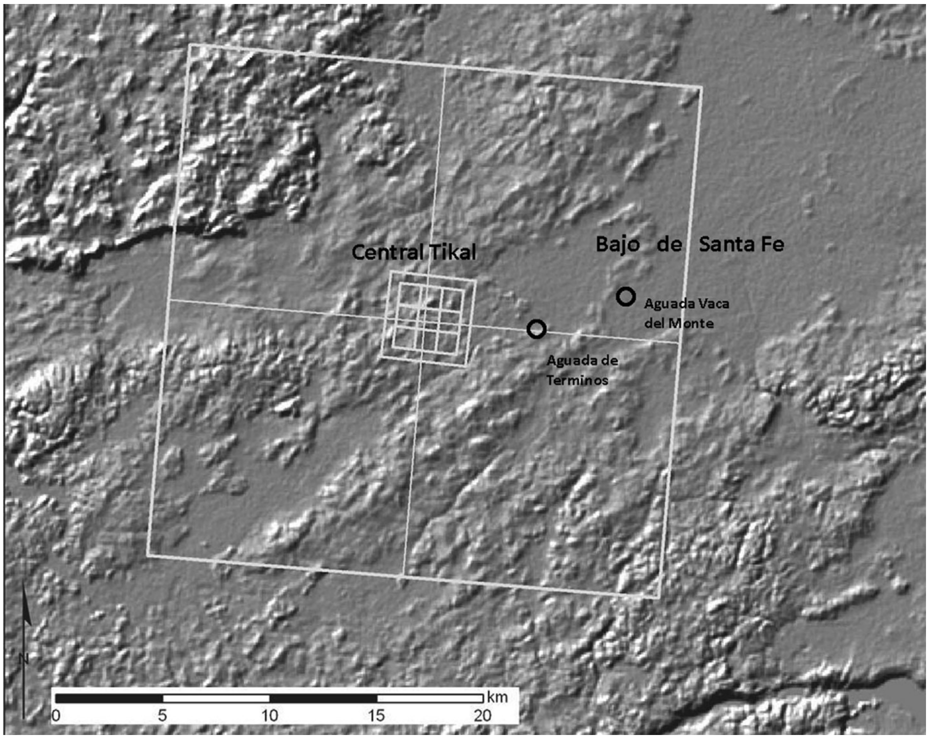

Fig. 4. Hillshade map showing the relationship of the Bajo Santa Fe to the site core of Tikal (on the left side of the image). The large square in white represents the borders of the Tikal National Archaeological Park and the smaller square inside that represents the area surveyed by the University of Pennsylvania in the 1960s. The *aguadas* shown in this illustration were the targets of intense sampling by this study (figure by Nicholas Dunning and Chris Carr).

2. Case study: Tikal environmental management practices

It is against the backdrop of these socio-political changes that three key forms of land use practice will be evaluated for their sustainability potential and their contribution to Tikal's imperial history. Undoubtedly, the agricultural practices, forest management activities and water control efforts of the Tikal residents were key components to the city's economic underpinning.

2.1. Agricultural investment

Extensive Preclassic agricultural practices were, through time, transformed into an intensified system that supported Classic period growth, but ultimately led to problematic environmental changes. In all likelihood, the initial Tikal inhabitants were primarily swidden agriculturalists. Pollen cores from Lake Peten Itza (Hodell et al., 2000) reveal a sharp decline in arboreal species during the Middle Preclassic period (700–350 BCE), indicating widespread forest clearance shortly after the time of Tikal's founding. This assertion is reinforced by observations of extensive erosion of soils that migrated into large karst depressions (*bajos*) surrounding Tikal at approximately the same time (Dunning et al., 2015). Until recently, reliable information concerning the array of plants grown at Tikal during the Preclassic period has been meager, but paleoethnobotanical studies conducted in the last several years revealed evidence for seed crops, e.g., maize (*Zea mays* L.) and scarlet runner bean (*Phaseolus coccineus* L.), root crops, e.g., achira (*Canna* cf. *indica* L.) and sweet potato (*Ipomoea batatas* [L.]Lam.), and tree crops, e.g., hogplum (*Spondias purpurea* L.) and coyol (*Acrocomia aculeata* [Jacq.] Lodd. ex Mart.) (Lentz et al., 2014, 2015). This set of cultigens most likely is only a partial list of the plants actually grown, but, nevertheless, it demonstrates that agriculture was important to the Preclassic inhabitants and they had enough crop variety to provide a nutritionally sustainable diet, i.e., with all the essential amino acids, vitamins, etc. Furthermore, they possessed the agronomic capability to exploit a diversity of habitats.

With population growth over time, the ancient agricultural system evidently expanded and gradually intensified. One of the most significant aspects of the niche construction activities of the ancient Maya at Tikal relates to their agricultural methods. As the settlement grew, its inhabitants actively extended the scope of their land use practices. To approximate the extent of the extractive zone of the Classic period Maya inhabitants, a Voronoi Diagram was defined by comparing Tikal's geographic position and relative population size to adjacent contemporaneous polities (Lentz et al., 2014, 2015). This extractive zone included 1,100 km^2 of mostly upland habitat that would have represented the landscape from which the Tikal residents extracted their basic necessities, outside of a few assorted trade items that were carried in by human porters or possibly transported by waterborne canoes in the rainy season. According to pollen data (Hodell et al., 2000), approximately 350 km^2 of this extractive zone was in managed upland forest. Settlement surveys (Fry, 2003) tell us that another 165 km^2 of the zone was a residential area likely planted in orchards and dooryard gardens, similar to what was observed at the Cerén site in El Salvador where a fine-grained understanding of Maya agricultural activities was achieved as a result of excellent preservation of crops and agricultural features caused by a thick layer of volcanic ash that covered the village in Late Classic times (Lentz and Ramirez-Sosa, 2002; Sheets et al., 2012; Farahani et al., 2017). The rest of the upland portion of the Tikal extractive zone, around 350 km^2, was devoted to extensive agriculture in some sort of short fallow cycle, probably employing ridge and furrow plantings (once again, as practiced at Cerén) along with other strategies to reduce soil erosion.

Major crop production at Classic period Tikal included maize, three species of beans (*Phaseolus* spp.), two species of squash (*Cucurbita* spp.), cotton (*Gossypium hirsutum* L.), and several species of root crops including sweet potato (*Ipomoea batatas* (L.) Lam.), achira (*Canna* cf. *indica* L.), malanga (*Xanthosoma sagittifolium* (L.) Schott), and probably manioc (*Manihot esculenta* Crantz) (Lentz et al., 2014). A variety of tree crops were cultivated, including cacao (*Theobroma cacao* L.) along with numerous other arboreal domesticates (Lentz et al., 2015). Most likely they planted cacao groves in special, protected niches with deep, humid soil. An example of such a place may have been the "Inscriptions Reservoir," which was not a reservoir at all, but more likely a *rejollada*, or deep karst sinkhole, where the trees could survive the dry season in a moist and protected setting (Dunning et al., 2015).

The *bajos* also played a role in agriculture. Approximately 80 km^2 (~30%) of the *bajo* forest was cleared for agriculture, mostly along the western fringes of the Bajo de Santa Fe (Fig. 4). The remaining 175 km^2 of the *bajo* area likely was used for intensive forest product extraction, e.g., for fruits, timber, fiber and medicine. It has been widely observed that many Late Classic Maya communities have been located on the edges of *bajos*, but why this is so, until recently, was largely a matter of conjecture. It now seems evident that the *bajos* were not just useful, they were, in fact, indispensable components of the food and forest product supply chains of Tikal (Lentz and Hockaday, 2009; Dunning et al., 2015). The pollen cores and geoarchaeological data from the *aguadas* at Vaca del Monte and Terminos, located in the western portion of the Bajo de Santa Fe (Fig. 4), demonstrate that these areas were used for the cultivation of maize, the root crop achira, and probably other crops as well.

In these seasonal wetlands, most agricultural activity occurred in the cumulic soils along the *bajo* margins (Balzotti et al., 2013; Dunning et al., 2015). Curiously, the colluvial soils that became the focus of Classic period intensive agriculture were at least in part created by accelerated soil erosion from adjacent uplands in the Preclassic period, when the land was first cleared of forest and cultivated. In excavations near the Aguada de Terminos on the fringe of the Bajo de Santa Fe, ancient top-soils were buried by Late Preclassic colluvium, which developed into highly productive soil formations, and offered an obvious sign of past forest clearance coupled with extensive agriculture (Dunning et al., 2015).

During the Late Classic period there are indications that the Tikal Maya found ways to address the erosion problem. The Classic period inhabitants, perhaps learning from the mistakes of their Preclassic ancestors, took great pains to protect the watersheds and were able to effectively reduce erosion, as seen in low sedimentation rates in the reservoirs (Lentz et al., 2015). For example, an examination of the sediment core from Corriental Reservoir reveals that the run-off into this feature, which has side wall slopes of 10° in some areas, had a sediment build-up of less than 2 $mm\ yr^{-1}$ during the Late Classic period and this was primarily aeolian, or wind-blown, sediment. Likely there was some preventative mechanism to control erosion and stop runoff from ruining the utility of the reservoir. One possibility was the maintenance of perennial vegetation, such as fruit tree plantations, in the areas surrounding the reservoirs (Lentz et al., 2015).

To further enhance the agricultural potential at Tikal, at least one reservoir, and likely several others, were used for crop irrigation. Perdido Reservoir, through an elaborate system of canals, received and impounded water from the "Lost World" plaza probably for use in agricultural irrigation during the dry season (Lentz et al., 2014; Scarborough and Grazioso, 2015). This may not seem like an exceptional development, but to the lords of Tikal the production of crops in the dry season when it was previously impossible and the ability to augment water supplied to crops during crucial developmental stages must have been an enormous boost to their productive capabilities and an extraordinary symbol of power. These efforts at agricultural intensification were an integral part of the socio-political history of Tikal.

2.2. Forest resource use

At Tikal, a conservative management of valued tree species apparently took place during Late Classic times as evidenced by burned wood remains from that period which are remarkably similar in terms of diversity and distribution to forest species common in the area today. This environmental practice can be considered a structural pillar in Tikal's economic and imperial history. Along with diachronic changes in agricultural techniques, the management practices of forest resources by the Maya inhabitants of Tikal also appear to have evolved over time. In cultural terms we know less about the Preclassic period than subsequent occupations at Tikal, mostly because the more recent phases of occupation were significantly larger and, in many cases, built on top of the earlier phases. What we do know about the Preclassic occupants of the Tikal area, however, is that they cleared extensive tracts of forests for agriculture as discussed in the previous section, but they also protected tracts of old-growth forest (Lentz and Hockaday, 2009).

As human populations grew in Classic times, maintaining forest resources would have been of critical importance for the sustainability of the community. Relying upon both paleoethnobotanical and modern forest ecological data, Thompson et al. (2015) observed that there was a measurable co-occurrence between the diverse archaeological wood remains found among the ruins of ancient Tikal and the oligarchic species (dominant trees) of the modern forest. These results suggest some type of low impact forest management practice likely was utilized by the Tikal Maya to preserve the most highly valued tree species and overall species diversity. For example, *sapodilla* was heavily exploited by the ancient Maya at Tikal (Lentz and Hockaday, 2009), yet the species continues as one of the dominant trees in the forest today.

Compare this to the European logging activities involving mahogany (*Swietenia macrophylla* King) during the 17th century in neighboring Belize (Thompson, 2004) where forest utilization practices were largely focused on the intensive extraction of a few species, unlike our Tikal example. As a result of those single-minded logging practices, mahogany, once a forest dominant, is today an infrequent or even rare species in Belize. In contrast, the evidence presented by Thompson et al. (2015) revealed that the forest management practices of the ancient Maya at Tikal were more strongly oriented toward sustainability, at least in terms of maintaining diversity.

The comparison of oligarchic trees to the non-oligarchic forest species in terms of their economic utility described in the ethnographic record is especially insightful. Almost all the tree species found in the modern forest are economically useful to one degree or another according to ethnographic accounts (Thompson et al., 2015). Indeed, the forest contains a considerable pharmacopoeia as well as timber and fuel supplies. Evidently, the ancient Maya found it in their best interests to maintain forest diversity to retain all useful timber and non-timber forest products.

Exactly how the Maya managed their forests is another question entirely and one at which we can only guess, but fortunately the paleoethnobotanical record combined with evidence from ethnographic accounts and modern forest surveys provide helpful clues. The first bit of evidence comes from the large Tikal temple lintels. These huge beams, most of which were cut from trees over 40 years old and some even older than 100 years, came from what was undoubtedly old growth forest. These enormous trees were felled to build Temples I, II and IV sometime between the late 7th and early 8th centuries (Lentz and Hockaday, 2009), long after the onset of the population centralization that began around 550 CE (Webster and Murtha, 2015). These old growth forests sat astride some of the most fertile agricultural land in the region, yet somehow were protected from over-harvesting in spite of intense population growth. There must have been some societal control that preserved these forest tracts and their stout arboreal denizens, otherwise the forests would have been quickly cleared and the soils exploited for agriculture. Possibly these old-growth forests were royal dynastic lands that were drawn upon for the mammoth temple construction projects that were designed to aggrandize the polity's greatest lords and appease the most powerful deities. This sort of forest reserve was hardly unusual in Mesomerica; Montezuma, the well-known Aztec ruler, had a royal forest set aside for hunting and other utilitarian purposes (Evans, 2000). In any case, the Tikal Maya exerted some degree of centralized control over their forests because their timber resources were carefully protected, at least until the 7th century CE when large trees were extracted for monumental construction projects (Lentz and Hockaday, 2009).

Another argument for forest management comes from the paleoethnobotanical data. The pollen record (Islebe et al., 1996) from Lake Petén Itza indicated a forest clearance in the upland areas that reached a removal plateau of around 60% of the forest cover. The Maya cleared over half of their upland forest, but appeared to maintain what was left. Examination of the paleoethnobotanical charcoal remains from Tikal revealed that over 90% of the charred wood samples collected had parallel rays. This indicates that the wood came from the trunks of mature trees, not branches or the boles of young saplings that would have been found in an intermediate term swidden situation. The evidence suggests they were managing mature forests and extracting their wood from large trees.

Our observations at Tikal indicate that the occupants used long-term strategies in a way that would preserve diversity. One possible model of how this could have been accomplished comes from medieval Europe, where foresters employed a partial felling technique or “umbrella felling” to maintain high forest canopies (*hochwald*). The main principle here is that trees would only be harvested if there was another tree in the area that could serve as the seed source or “umbrella tree” to provide the germplasm for replacements (Schulze et al., 2002). This strategy allows continual harvesting but conserves biodiversity. If confirmed, this Maya use of umbrella felling may be the earliest example of the practice. The challenge of cutting down a tall forest tree with a stone ax also seems daunting, but a culture that managed to build 50 m tall stone temples also could fell trees using a combination of girdling, cutting and burning. Why they managed these forests so carefully is not hard to explain: they needed the wood and the other forest products. Their forests were their main fuel source, a major habitat for forest animals and an important source of construction material, gathered foods and medicinal plants. It is also possible that the Tikal Maya engaged in these long-term conservation practices because they had an enduring cultural memory from Preclassic times when cutting down extensive swaths of forest proved to be a deleterious practice.

The model presented herein is largely based on archaeological and paleoethnobotanical data. Other models for ancient Maya agriculture and forest management (e.g., Ford and Nigh, 2009) are largely based on modern and historic ethnographic data. During Spanish contact times the Maya essentially used a long-term system of swidden cultivation and many Maya groups still practice this form of agriculture and forest management today (Jones, 2000). When practiced with long cycle times, swidden agriculture is definitely a system that can be used sustainably in the neotropics, but a 20-year fallow cycle takes an enormous amount of land per capita to manage effectively. If the amount of land available to the ancient Late Classic Maya of Tikal as a resource extraction zone calculated by the authors of this paper is anywhere near correct, then there was simply not enough land to employ a forest garden approach with a 20-year fallow cycle that would feed the multitudes of Late Classic Tikal. In addition to the issue of extensive swidden, the ancient Maya used other kinds of agricultural intensification practices; they built terraces (Chase and Chase, 2017), constructed canals and reservoirs for irrigation (Lentz et al., 2014; Scarborough and Grazioso, 2015) and practiced ridge and furrow agriculture (Sheets et al., 2012). In short, the modern Maya practice agriculture somewhat differently than the Classic period Maya and although ethnographic analogy is always useful, ethnography and historical accounts of contact period Maya alone cannot fully explain land-use practices of the past.

Intriguingly, there is new evidence from researchers in South America indicating that extensive forest clearance, even as little as 50% of the trees, may negatively impact rainfall patterns (Georgescu et al., 2013; Cook et al., 2012). Forest clearance in the tropics dramatically affects transpiration rates and hydrologic cycling, so it is quite possible that the Tikal Maya and their numerous neighbors, who cleared approximately 60% of their upland forest, may have unknowingly contributed to the devastating droughts of the Late Classic period.

2.3. Water management

The Preclassic Tikal Maya likely obtained their drinking water from the high spring or springs, at least one medium-sized reservoir (Corriental), and from *aguadas* in the *bajos* that were anthropogenically created or enhanced (e.g., Terminos) to retain additional water in the dry season. Based on this land use strategy, Tikal developed into a sizable community, with perhaps 10–15 thousand inhabitants by the second century CE. At the end of the second century CE, the Terminal Preclassic, the Maya Lowlands underwent a period of increased drought severity and frequency as mentioned above. The Tikal polity survived this period of political and environmental upheaval probably because the freshwater springs of the site core continued to produce potable water and the Corriental reservoir and the *bajo aguadas* retained adequate supplies of water to get them through the dry seasons. They had a variety of crops, especially root crops, that would have given them adequate agricultural options. Also at this time, there were adequate forest resources to support what was still a relatively small human population.

With increased population growth during the Classic period, the procurement of adequate water supplies became an even more crucial need for the Tikal occupants to survive in the seasonally arid interior Maya Lowlands. For the polity to expand and accommodate larger populations, the water management practices had to expand and evolve (e.g., Dunning et al., 1999; Scarborough, 1994, 1998; Scarborough and Burnside, 2010; Scarborough and Gallopin, 1991). The role of paved and slightly canted surfaces designed to shed abundant seasonal runoff from the great plazas and courtyards into the several large reservoirs throughout and below the site core of Tikal (Fig. 5) undoubtedly was another key component of water management (Scarborough and Grazioso, 2015). Three of these reservoirs were created by damming the ravine where at least one spring served as the source of water for the Preclassic founding community near a high point in the regional topography. The Classic period Maya initially sought to impound water flowing out of the springs using cut-stone walls or dams, then attempted to enhance the water source by paving the hilltops surrounding the ravine and redirecting rainfall into the reservoirs. Because the reservoir system was so thoroughly integrated with the major civic ceremonial precincts of the city, the planning of these construction projects must have been under the control of the elite leadership. Furthermore, these artificial water systems were key elements in the expansion of the population of Tikal and the development of the imperial city. Ultimately, though, the extensive construction built around each reservoir may have limited the recharge capacity of the springs (Scarborough and Grazioso, 2015). This made the Late Classic Maya even more dependent on annual rainfall to maintain adequate water supplies during the dry seasons.

At the Terminos settlement, by contrast, chert debris was used to construct terraces in an effort to retain moisture and conserve soil resources in an intensified agricultural context that was likely under local supervision (Dunning et al., 2015). Notably, this humble suburban settlement on the *bajo* fringes of Tikal seems to have outlasted the great civic ceremonial center. The remote settlement continued well into the Postclassic period, long after the site core of Tikal was abandoned. Quite probably their anthropogenically-modified *aguada* remained viable (it remains a fairly dependable water source today), allowing the inhabitants to survive while others at Tikal perished or moved on.

When the multi-year droughts of the Late Classic period in the mid-9th century commenced, the polity of Tikal must have been subjected to considerable strain. Water levels in the reservoirs surely dropped. Maize and other crops may have failed and, as described by Webster and Murtha (2015), the ancient Maya had no major granaries or other means of storing large quantities of food. Food storage was likely on a local level with each farmer storing his own surplus (cf. Scarborough and Valdez, 2014). This was a tenuous arrangement, at best, with a probable storage technology that could preserve food for around three

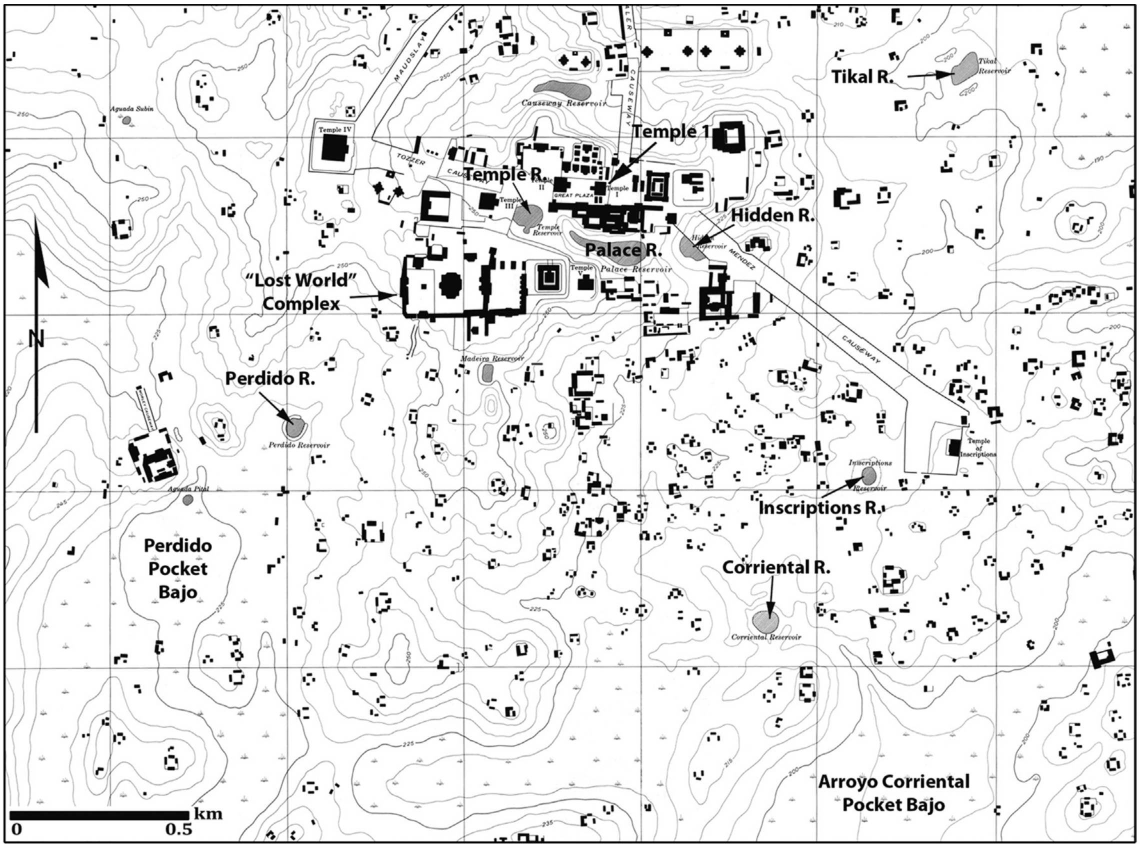

Fig. 5. Map of the site core of Tikal showing the location of many of the reservoirs and other features discussed in the text (figure by Chris Carr).

years (Smyth, 1991). Even if the Tikal Maya were fully prepared for a drought, their food supply could have lasted only three years and their reservoirs may not have retained water that long. A drought longer than three years, as hypothesized, would have resulted in mass starvation at, or exodus from, Tikal.

3. Discussion: Sustainable polity?

Applying the fundamental principles of resilience and panarchy theories to the vulnerabilities and resilient capacities of ancient Maya Lowland communities, it is likely that communities located in the EIR, e.g., Tikal, were significantly more susceptible to collapse and faced greater obstacles for effective reorganization than the surrounding low-lying areas with perennial water sources (Dunning et al., 2012). While system rigidity and the vagaries of a strictly hereditary, ruler-centric political organization likely plagued all Maya urban society (Coe, 1967; Lucero et al., 2011), the extreme dependence on rainfall, water capture and storage made polities within the EIR especially susceptible to drought and other climatic shifts. This acute dependence on local rainfall made the Maya polities in the EIR subject to sudden population loss, and also made it less likely that these communities could recover when the drought was over.

Undoubtedly, the calamity of water and food shortage had a destructive effect on social order as seen in many parts of the Maya Lowlands (Lucero, 2002, 2006a, 2006b; Lucero et al., 2017) and this societal breakdown may have been the immediate cause of the abandonment at Tikal. Indeed, what kind of leadership could have successfully managed a major urban center, already at or exceeding its agricultural potential and then confronted with an extensive period of increasing climatic aridity? It was the ruling elite's responsibility to offer spiritual leadership and sponsor public ceremonies, feasts and other integrative activities for their subjects, as well as provide adequate supplies of food and drinking water. In the face of prolonged drought, the rulers were unable to meet public expectations and lost their powers over their populace (Lucero et al., 2011). As a result, public confidence surely waned and people left in the wake of a deepening drought. The city was already experiencing steep population losses by the time Stela 11 was erected in 869 CE and soon thereafter the once glorious palaces of the Central Acropolis were occupied by squatters (Culbert, 1973; Harrison, 1999; Martin, 2003).

If we apply the precepts of resilience and panarchy to the city of Tikal through its long arc of occupation, then the processes of development and systemic change in their adaptive cycles come into clearer focus. The early Preclassic was clearly a time of expansive exploitation (r phase) of the natural environment when pollen evidence reveals a rapid removal of forest cover (Hodell et al., 2000) in what appears to have been a broad scale slash-and-burn exploitation of soil and forest resources. As time went on, the inhabitants of Preclassic Tikal moved into a conservation phase and began to invest in capital improvements, notably reservoirs specifically aimed at risk management and some cut-stone monumental architecture. The droughts of the second century CE evidently forced the Preclassic occupants into a release phase (Ω) in which subsistence must have become more tenuous. Fortunately for the occupants, the population was low and their access to unexploited forest and *bajo* resources was considerable. Also, they had invested somewhat in water conserving infrastructure so they were able to endure through this period of low precipitation.

The Terminal Preclassic climatic downturn likely created an indelible memory for the Tikal inhabitants who survived the upheaval. In the subsequent Early Classic period, they began to reorganize and invest in extensive reservoir construction projects, undoubtedly having learned that large reservoirs are quite valuable in times of drought. Also, they adapted their agriculture to reduce erosion and adjusted their forest use practices to harvest timber resources more sustainably. Perhaps it was the collective memory of widespread erosion in the Preclassic period that encouraged the Classic period Maya to adopt a more conservative approach to forest management. As the population continued to grow, agriculture became more intensified with a shortened fallow cycle. Furthermore, they began to use *rejolladas*, terraced fields, canals and reservoirs devoted, not only to the retention of drinking water, but for use in irrigation, as well.

As Tikal regained its hegemony over the trans-isthmus trade routes at the beginning of the Late Classic period, circa 700 CE, a spectacular episode of temple and palace construction ensued unlike the Maya realm had ever seen. Along with this massive construction boom came yet additional population growth and a system with greater interconnectedness and capital infrastructure. Indeed, Tikal became overconnected through landscape niche construction, intensive water management and a hegemony of regional trade and political networks. The lords of Tikal accumulated high levels of capital in what was essentially a K phase of the adaptive cycle. As a result, they exerted unprecedented power over the occupants of the polity as well as the surrounding socio-ecological system. All of this transpired when the Maya Lowlands experienced a long period of above average rainfall.

The release point of this K phase came about 150 years later when yet another series of severe droughts brought this magnificent, but ecologically over-extended, community to its knees. Its entire system of water management and agriculture was based on yearly rainfall, without it there would have been inadequate supplies of drinking water and food, especially during the dry season. The rigidity of the Maya political organization, coupled with the acute dependence on water capture and storage, made Tikal and other polities within the EIR especially vulnerable to drought and other perturbations, while expanded populations rendered recovery less likely (Dunning et al., 2012).

Notwithstanding the elaborate water retention and irrigation systems of ancient Tikal under the control of the ruling elite, this complex infrastructure failed in the face of extended low rainfall while the simple, modified *aguada* near the Terminos settlement, which was under local control, remained sustainable through the Terminal Classic and into the Postclassic. This is an example of how centralized, top-down hydraulic systems are not always the most effective in the long run. At least in this case, locally controlled agricultural and water management systems can prove to be more sustainable over extended periods of time.

During the droughts of the 9th century, the city of Tikal, along with many other communities in the EIR, shifted abruptly into a release phase. Resilience and panarchy theorists may call this the “collapse” or a “revolt” part of the adaptive cycle, but we see this more accurately described as a reorganization. While it is true that there must have been a collapse of the political structure at Tikal where the rank and file lost faith in the ability of the leadership to successfully mediate the relationship with the Maya gods and environmental circumstances, there is no evidence that there was a violent revolt among the populace. More likely, the critical shortages in water availability cascaded into other aspects of the economic, social and political infrastructure. The end may have been a scenario where the occupants either died or left the city. Likely they moved to areas outside the EIR with permanent water sources (Gunn et al., 2016). Most interior communities were eventually abandoned and the trans-isthmus trade routes shifted to water routes that moved goods around the Yucatan peninsula rather than across it (Turner and Sabloff, 2012) in what became a massive reorganization of the ancient Maya world.

A remarkably similar scenario to the socio-political trajectory of Tikal has been recorded for another civilization in a wet and dry tropical environment on the other side of the globe. The Khmer Empire, located in the Mekong Delta of what is now Cambodia began an r-phase of development sometime around 500 BCE. It had a low density settlement pattern and the occupants relied primarily on rice produced in rain-fed fields, flood recession areas, and floating fields. They built canals and small reservoirs that mostly focused on irrigation. Green spaces and orchards were maintained, but extensive forest clearance was commonplace along with concomitant erosion. Their capital was Angkor Borei, an urban center based on a highly decentralized agrarian infrastructure where stelae, written in Sanskrit, began to appear in the 7th century CE. Shortly thereafter, however, this “protostate” collapsed due to a variety of external and internal causes (Iannone, 2016).

After a period of reorganization, a new “charter state” emerged around 800 CE in a K-phase of development characterized by demographic growth, massive architectural construction (both secular and sacred) and agricultural production enhancements, i.e., canals and reservoirs. These developments were greatly aided by the Medieval Climate Anomaly, a period of unusually high rainfall which lasted from 800 to 1300 CE. As the population increased, the hydraulic enhancements were expanded into marginal lands to meet growing food needs. This expansion led to a risk spiral with a massive increase in infrastructure and increased forest clearance accompanied by loss of topsoil, erosion and sediment build-up. When the drying trend began in 1250 CE, enormous ecological and economic problems ensued: agricultural productivity declined and maintenance began to outstrip resources. It was not long until Angkor and the Khmer hinterlands suffered a tipping point and societal collapse (Ω phase). Following this, a reorganization occurred (α phase) in the form of a diminished, balkanized, social state occupying a degraded landscape, a pale shadow of the magnificent Khmer Empire. All of this took place as new centers of commerce, such as Phenom Penh, emerged near the coast.

The parallel cyclic trajectories of the Tikal Maya and the Angkor Khmer are remarkable. They were both enabled and constrained by their tropical ecosystems characterized by high biodiversity, seasonal rainfall and soils that readily lose nutrients when tree cover is removed. In both cases, the nature of their surrounding environments and climate change were major stress factors in each societal demise. They both underwent expansive population growth, expanded their architectural epicenter and increased their agricultural capacity through landesque capital construction during periods of high rainfall only to face insurmountable crises when a period of systemic dryness followed. The value of resilience theory is categorically revealed when comparing the similarities of the adaptive cycles of these two iconic ancient cities.

4. Conclusions

The ancient Maya of Tikal, much like the Khmer of Ankor, engineered a constructed niche that was designed to provide sustenance and fuel, using existing technology, for as many people as possible within the bounds of the territory they controlled. The Late Classic Maya had maximized the productive potential of their constructed niche in the heart of the Petén tropical forest during the relatively stable periods of above average rainfall during the 7th and 8th centuries. These large-scale Maya landscape alterations placed excessive demands on local ecosystem services and this in turn generated high-stress environmental circumstances that, eventually, were exacerbated by increasing climatic aridity (Turner and Sabloff, 2012). It now seems likely that the rapid depopulation of Tikal during the Late Classic period resulted from the intersection of a subsistence strategy that was already at, or perhaps beyond, the edge of sustainability combined with a period of extended low rainfall and a rigid social structure that lacked the capacity to effectively adapt to changing circumstances. Moreover, it is quite possible that their forest clearance activities, even though conservative in many respects, helped to bring about the period of attenuated precipitation. The environmental changes that transpired exceeded their ability to compensate and this impasse brought about the end of the Late Classic splendor at Tikal.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jaa.2018.08.005.

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