Classic Period collapse of the Central Maya Lowlands: Insights about human–environment relationships for sustainability

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The ninth century collapse and abandonment of the Central Maya Lowlands in the Yucatán peninsular region were the result of complex human–environment interactions. Large-scale Maya landscape alterations and demands placed on resources and ecosystem services generated high-stress environmental conditions that were amplified by increasing climatic aridity. Coincident with this stress, the flow of commerce shifted from land transit across the peninsula to sea-borne transit around it. These changing socioeconomic and environmental conditions generated increasing societal conflicts, diminished control by the Maya elite, and led to decisions to move elsewhere in the peninsular region rather than incur the high costs of maintaining the human–environment systems in place. After abandonment, the environment of the Central Maya Lowlands largely recovered, although altered from its state before Maya occupation; the population never recovered. This history and the spatial and temporal variability in the pattern of collapse and abandonment throughout the Maya lowlands support the case for different conditions, opportunities, and constraints in the prevailing human–environment systems and the decisions to confront them. The Maya case lends insights for the use of paleo- and historical analogs to inform contemporary global environmental change and sustainability.

Mesoamerica | complex systems | land management

Forty years ago, a gathering of Maya scholars concluded that the demise of the Classic Period Lowland Maya was the result of complex systems interactions (1).* Such conclusions neither grab headlines nor support interpretations that emphasize one collapse factor over others, such as climate change (2–6). They are, however, consistent with the emerging understanding of complex adaptive systems (7), in which interactions among subsystems may reach tipping points or thresholds that trigger systemwide collapse and reconfiguration. For human–environment systems, collapses and reconfigurations can lead to socioeconomic and political demise and in some cases, area abandonment (8). Such events, however, involve societal decisions about the use and maintenance of the environment, elevating the complexity involved in understanding human–environment outcomes (9). For these reasons, the use of paleo- and historical human–environment collapse as analogs to inform global contemporary environmental change and sustainability must treat generic system behavior and site-specific system properties equally (10). Systemwide thresholds seem to have been reached throughout much of the Maya Lowlands of the greater Yucatán peninsular region (Fig. 1) in the Terminal Classic Period [Common Era (CE) 800–1000] but especially, in the first 50 y of this period (11, 12). Not only is a cultural collapse registered at this time, indicated by the demise of many city-states and cessation of certain forms of monumental architecture, but a large proportion of the population of the Lowlands simply disappeared (13, 14).

Substantial variation in occupation, however, existed among different areas and city-states throughout the Lowland Maya realm during and subsequent to the Terminal Classic Period, with strong continuity and even florescence in some locations (15–17). The Terminal Classic Period, therefore, did not mark the end of pre-Columbian Maya civilization—the 16th century Spanish Conquest did (18). For this reason, some scholars have been reluctant to use the term collapse to describe the ninth century events in the Maya Lowlands (19, 20), consistent with recent cautions, advanced in this journal, about the use of collapse themes in general to inform sustainability concerns (21). The Central Maya Lowlands (CMLs) (Fig. 1) and its large infrastructure of cities, water systems, and managed landscapes, were essentially abandoned, however, with population declines approaching 90% (14), and it remained so for well over a millennium. In this sense, the term collapse is appropriate.

Multiple lines of research addressing the human–environment system present during the collapse and depopulation of the CMLs suggest that complex feedbacks and synergies were at play, in which socioeconomic factors were as important, if not more important, than environmental factors. Matching this understanding with evidence from the Postclassic and historic Maya periods (CE 1000–1600) provides a picture in which the economic focus and concentration of wealth among the Maya shifted from the interior uplands (see below) to the lower-lying coastal shelves and inland waterways of the Yucatán peninsular region (12). It was this distribution of occupation that the Spaniards encountered on their arrival in the early 1500s (22). The interior uplands, in contrast, remained sparsely occupied and covered by older growth forest.

A review of the paleoenvironmental, archaeological, and historical evidence, combined with information on contemporary forest and forest use dynamics in the region, provides insight into a revised model of the collapse event. This evidence points to human–environment interactions precipitating the social, political, and cultural decline and depopulation and long-term abandonment of the former Classic Period heartland (23). Indeed, the subsequent protracted period of low-density settlement generated the forested landscapes that the Calakmul Biosphere Reserve of Mexico and the Maya Biosphere Reserve of Guatemala, parts of the Mesoamerican Biosphere Reserve, seek to protect today.

CMLs: Human Occupation and Environmental Background

By the Classic Period (CE 300–800), the Lowland Maya were a highly complex civilization organized into networks of city-states that ranged across the entire Yucatán

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*J.A.S. participated in the conference that generated the complex collapse thesis.

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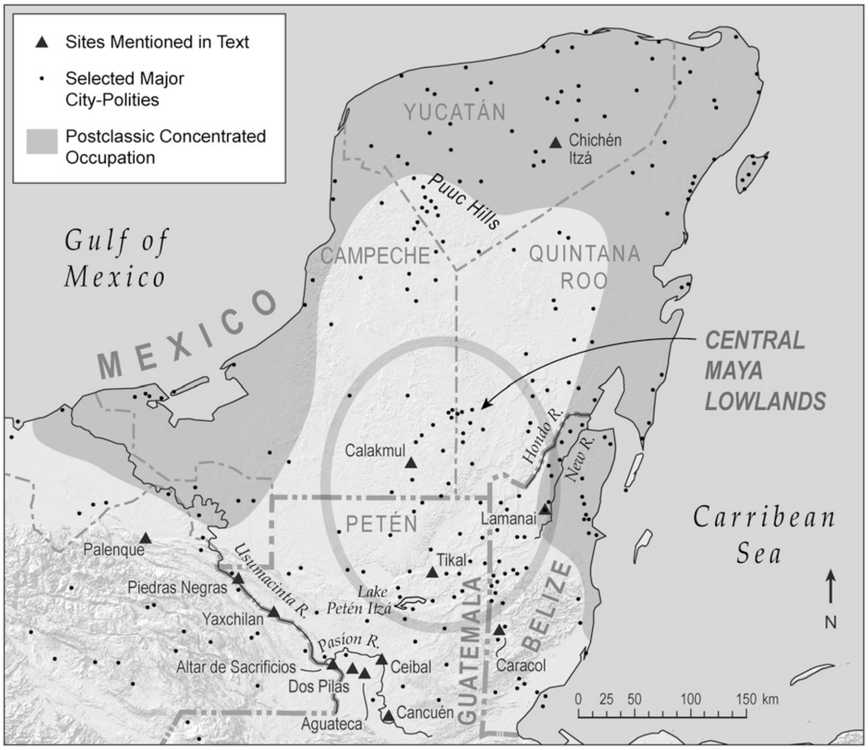

Fig. 1. The CMLs and Lowland Maya Realm. Modified from refs. 95 and 113.

peninsular region, extending south between the Caribbean Sea and the Usumacinta watershed to the highlands of current day El Salvador, Honduras, Guatemala, and Chiapas, Mexico (~700 km north to south and 450 km east to west). The area designated as the CMLs encompassed much of current day northern Petén, Guatemala, southern Quintana Roo, Campeche, Mexico, and adjacent parts of Belize (Fig. 1). This physiographic area may be considered the heartland of the Classic Period Maya based on the number of large city-states concentrated there, including Tikal and Calakmul, and the overall level of habitation, with estimated population densities >100/km^2 throughout much of it (13, 14).

This heartland is an interior hilly region situated on the upland spine of the Yucatán Peninsula, a karstic plateau rising to maximum elevations between 350 and 400 m above sea level and about 150–200 m above the coastal shelves along the Caribbean Sea and Gulf of Mexico. The rolling landscape is interspersed with large sinks or depressions. A north–south ecocline follows a precipitation gradient of ~900 to >1,400 mm (annual average), in which a distinctive winter dry season prevails. The uplands support a seasonal tropical forest residing on fertile but thin Mollisols, typically 50 cm in depth, whereas thick montmorillonite clays, up to 1 m or more in depth, fill the depressions, collecting wet season precipitation and runoff to generate seasonal wetlands. Fault- and solution-generated lakes exist, especially on the southern and eastern edges of the CMLs, and rivers also exist, especially below 100 m elevation. For the most part, however, the hilly heartland is devoid of permanent streams but maintains a few scattered shallow water bodies, mostly small solution depressions with no outlets, and occasional springs. Most aquifers are deep, in excess of 100 m or more below the surface. The paucity of surface water is amplified by decade- to century-long droughts that have characterized the peninsula throughout its occupation (24).

In the tropical wet–dry climates of the CMLs, annual averages in precipitation are less telling than the length of the period in which evapotranspiration exceeds rainfall (25). The severity of seasonal dryness increases north in the peninsula, but it varies annually by location. Deciduousness during the height of the dry season (March to April) is the adaptation mechanism of forests, the southern extent of which varies somewhat year to year. Today, deciduousness is recorded as far south as the middle of the heartland (about the Guatemala–Mexican border) (26).

Forests are disturbed by persistent hurricanes from the Caribbean Sea, and the eastern portion of the CMLs receives the brunt of hurricane damage (27). Less common tree species seem to have higher mortality to hurricanes than common species (28), and damaged and dead forest vegetation is prone to unintentional fire outbreaks. Phosphorus (P) seems to be the limiting nutrient for vegetation, with critical inputs captured by the forest canopy and washed to the soil, creating a positive feedback between old growth canopy and available soil P (29). A flurry of recent work indicates that virtually all P in the CMLs is exogenous in origin (as much as 25% from wind-blown Sahara dust), that older-growth forest traps fourfold more P than opened lands, that repeated swidden (slash and burn) cycles lower P and biomass in subsequent forest regeneration, and that decreased soil moisture lowers the available P (29–34).

Opened land, especially land that is repeatedly burned, is commonly invaded by bracken fern (*Pteridium aquilinum*), creating a positive feedback between fern persistence and burning (35, 36). The fern is difficult to eradicate, especially if the landscape remains open and burning is commonplace. Frequently cutover land also gives rise to a degraded forest in terms of species richness, and it stymies the regeneration and maturation of hardwood species for which these forests are noted (37).

There is increasing evidence that the scale of modern forest removal, far less than the scale at the time of the collapse (38), reduces local to regional precipitation (39–41). This finding is supported by data indicating that secondary forest maintains more soil moisture than older growth, presumably because the former, with less canopy cover, releases less moisture to the atmosphere (37). Recent modeling work also shows that more open land in the Maya area increases surface temperatures and reduces precipitation (42).

The ancient Maya also confronted long-term climatic aridification, experienced as century-level or longer droughts (43). Multiple lines of evidence in the paleoclimate archives support this observation, the dating of which reveals that long-term spikes in aridity coincided with the various hiatuses in the Maya ascendency to their Classic phase (44–47). The most extreme spike in climatic aridity (CE 750–1050) coincided with the end of the Classic Period and widespread depopulation, especially in the CMLs (43, 48). Recent δ^{18}O analysis of stalagmites from the Yucatán indicates that the Terminal Classic Period was wracked by eight severe droughts of 3–18 y in length, in which precipitation declined by 36–52% below long-term averages (49) through major declines in the summer tropical storm frequency and intensity [the work by Medina-Elizalde and Rohling (46) concludes that prolonged drought interludes up to and through the Classic Period collapse approached no more than a 40% reduction in annual average precipitation, an amount that the work labels as modest (50)]. Precipitation increased subsequent to the collapse, except during another dry interlude in the 15th century that coincided with the Little Ice Age (51, 52).

Human–Environment Interactions

Occupation of the CMLs initially focused on clearing forests on better-drained Mollisols, apparently moving from extensive forms of swidden or slash-and-burn cultivation to more diverse and intensive management practices as land pressure mounted. The paleoecological record indicates large-scale deforestation increasing throughout the Preclassic Period (with noted pauses at the end of the Middle and Late Preclassic Periods), which was registered by substantial declines in forest pollen (53–55) and increases in disturbance and maize pollen as well as evidence of increased spores (presumably fern) (38, 56, 57). During this period, forest clearing, its burn footprint perhaps enlarged by drought, generated substantial soil loss from upland slopes (58–60) and sediment runoff onto the coastal shelf, especially in the riverine environments of northern Belize (61). Land pressures, of course, varied spatially and temporally across the heartland, but after a population growth hiatus at the end of the Late Preclassic Period, overall land pressures mounted again. Substantial use of terracing on upland slopes began in earnest in the Early Classic Period (59), a land management technique that apparently reduced erosion and loss of soil nutrients through cultivation (58). In general, by the Late Classic Period, Maya settlements, large to small, were distributed across the heartland, and all forms of Maya cultivation and land management were in use in an open landscape consisting of a mosaic of land uses and covers (62–64). Larger city-states, such as Tikal and Calakmul, exceeded populations of 50,000 and maintained large amounts of monumental architecture, elite residences, markets, reservoirs, and manipulated seasonal wetlands (65–73). Caracol, on the edge of the CMLs in Belize, had a Late Classic population well in excess of 100,000 (74). Rural hamlets were ubiquitous, complete with house-lot orchard gardens, and surrounded by terraced and walled fields (59, 75–77) or wetland fields (78–82), especially just off the uplands (below 150 m asl), and managed forest (22, 83, [†]).

The elements of this landscape are well-documented and need not be reiterated in detail here (23, 38, 44). Some of the evidence is direct, such as the evidence for settlements and monumental architecture, terraces, and wetland fields. Other evidence is indirect, including orchard gardens, managed forests, and possible cultivation along modified edges of seasonal wetlands (66). The evidence for orchard gardens is based on the archaeological record of vegetative remains in middens, suggesting a long history of a strong reliance on fruits and nuts (84–87), and walled spaces around house sites, indicating orchard gardens as described by the Spaniards (83, 88). The abundance of economic species found today among Maya ruins (89) and in some forests in general, recorded as early as the first part of the 20th century (84, 90, 91) and consistent with ethnohistoric records of Maya forest management (92, 93), supports the case for orchard gardens and managed forests. The sheer size of the population and plastered surfaces in the heartland would have required large amounts of fuel for cooking and preparing mortar, placing large demands on forest biomass (94) and water, especially during the latter stages of the dry season (65, 71).

Although occupation and land use varied across space and time (41, 95), by the Late Classic Period, the paleoecological evidence points to a landscape under stress (96). It documents massive reductions in arboreal pollen on the order of 90% (53–55, 60) and large increases in disturbance indicators, including maize and fern spores (56), perhaps bracken fern. In addition, the favored construction beams for monumental structures, wood of *Manilkara zapote*, ceased to be used at Tikal and Calakmul about CE 741. The wetland species *Haematoxylon campechianum* (logwood) served as a substitute until about CE 841, when much smaller zapote was again used (97). Managed or not, the combined human and environmental stresses on forests reduced the habitat and maturation time for mature zapote growth (37). Other construction evidence of major forest loss is the substitution by the Late Classic Maya at Palenque of inferior clays for lime in plaster, indicating that insufficient biofuels were available to generate lime (49). Likewise, recent evidence indicates that larger mammals, especially the white-tailed deer, declined in zooarchaeological assemblages across the Maya domain during the Late Classic Period and beyond (98–102), suggesting a combinations of stressors, such as overhunting and loss of forest-edge habitat.[‡] It should be noted that these and other Maya-induced indicators of environmental stress were escalating in the face of a protracted period of climatic aridity, culminating in the Terminal Classic Period.

Environmental Stress Model

Environmental considerations of the collapse of the CMLs must be tempered by the realization that the Maya occupied the area for more than 2,000 y, a time in which they developed a sophisticated understanding of their environment, built and sustained intensive production systems, and withstood at least two long-term episodes of aridity before the Late Classic Period. This caution notwithstanding, a number of important stress points apparently developed in the land use systems of the CMLs (Fig. 2).

By the Late Classic Period, if not before, the majority of the upland forests of the heartland had been cleared for cultivation and settlements, both large and small, although orchard gardens were ubiquitous and managed forests apparently existed, perhaps serving as buffers between the hinterlands of city-states (Fig. 2). This reconfiguration of the landscape initiated a number of problems (see above) (23). Loss of forest canopy decreased the capture of P, the limiting soil nutrient, from the atmosphere. Maintaining cleared land most likely involved burning, a practice that favored bracken fern invasion. The large number of settlements of all sizes increased impervious surfaces throughout the Lowlands and in tandem with increasing amounts of cultivated land, led to greater sedimentation and loss of soil nutrients. Such land degradation triggered a flush of upland sediments into the riverine wetlands along the lower courses of the Hondo and New rivers in Belize and perhaps, the portion of the Usumacinta watershed of Mexico adjacent to the heartland. It is in these locales that confirmed Late Classic wetland agriculture was undertaken by the Maya. Regardless, sediment loss was substantially reduced by cropping practices instigated in the Early Classic Period, such as the use of terraces on slopes. Despite managed forests, wood fuel and construction timber became increasingly scarce as did, perhaps, large mammals (meat sources). To maintain a sufficient water supply, small aquadas (ponds) and major reservoirs were constructed, and the edges of seasonal wetlands were manipulated to hold water (65, 66, 69, 71).

By the beginning of the Terminal Classic Period (CE 800–1000), the land systems of the heartland, many of them intensive in kind, were millennia in the making. Maintaining the infrastructure in place and combating the drawdown in environmental conditions (e.g., loss of P) required

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[†] The identification and interpretation of wetland fields on the peripheries of the Maya heartland have been contentious not in terms of the presence and past Maya use of the fields but rather, in regard to their morphology, construction, and somewhat less so, dating (61, 66, 72, 81). It is noteworthy that these systems adjacent to the CMLs in Belize, even those systems in perennial wetlands, ceased with onset of collapse (79).

[‡] It is noteworthy that the zooarchaeological evidence is sparse, and the studies to date suggest regional heterogeneity in forest habitats supporting deer based on assessments of bone assemblages (98–102). Much of the evidence comes from the lower Usumacinta–Pasíon watersheds, which may have maintained more intact forest and forest edges than the forest that was present in the CMLs.

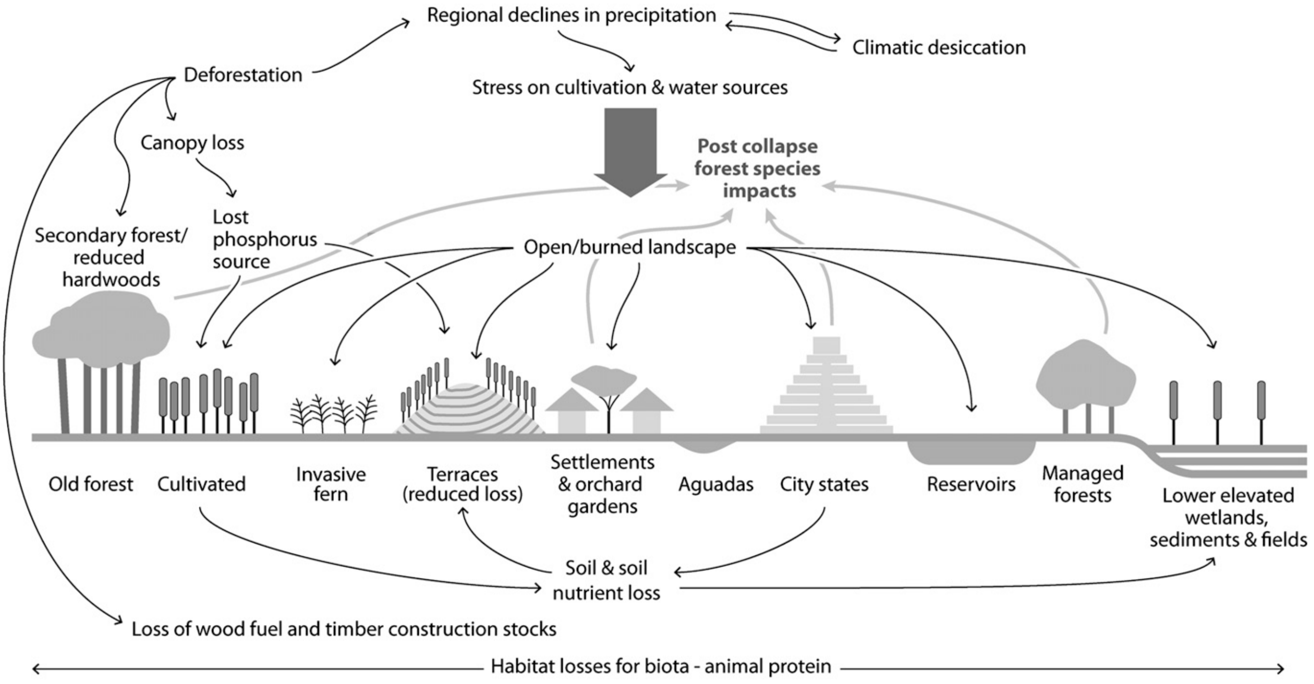

Fig. 2. Human–environment dynamics in the CMLs.

major levels of inputs, including labor, manure, and mulch. Coinciding with these conditions was a spike in climatic aridity, which combined with the landscape impacts on evapotranspiration, produced moderate to severe precipitation declines. Surely such declines stressed the human–environment systems of the heartland, including having impacts on P through reduced soil moisture and canopy regrowth, and, in general, requiring major resource adjustments and inputs into the food, fiber, and water systems (71). The critical question is, of course, were these stresses sufficient to generate a tipping point in the human–environment system that, after crossed, led to a cultural collapse and depopulation? Recall that the CMLs had encountered several such desiccation episodes in its history of occupation, each registered as momentary lapses in the ascendency to Classic Period conditions. This time, perhaps, barriers to maintain or grow the system were so large that they favored decisions not to do so.

Beyond Environmental Stress

These decisions involved more than the immediate food, fuel, fiber, and water consequences of the stressed human–environment system. They were also situated in the socioeconomic, political, and ideological dimensions of the Maya. Foremost were the costs of legitimizing elite power, which apparently became particularly burdensome over time. The elite constituted a very small percent of the population but maintained significant authority and power, with major disparities in wealth and standard of living over the vast majority of the population. The elite likely controlled vital resources and trade as well as advanced knowledge (i.e., literacy, math, astronomy, and engineering), military power, and links to the gods (103). For this control and the entitlements that came with it, they were expected to provide material, spiritual, and ideological security (104). Successful problem-solving must have become the key issue for ruling elite given the human–environment conditions of the Late Classic Period.

In addition to those problematic conditions, the economy of trade seems to have changed as well. The ascendency of the CMLs relative to other parts of the Maya realm may have been linked to its control of trade from the Caribbean and Central America to the Gulf of Mexico and central Mexico, which apparently was routed across the CMLs (105). By the Terminal Classic Period, this trade seems to have moved by sea around the peninsula more than ever before (106–110), including such goods as obsidian, many of the sources of which were located inland. This shift in commercial transport, of course, could have been an outcome of the collapse of the CMLs, but its role in reducing the financial coffers of area's city-states, thus rendering landscape-level upkeep extremely difficult given all of the other costs, warrants attention.

One such other cost was maintaining and legitimizing the authority, power, and wealth of the ruling elite. Recall the amount of infrastructure and labor required to manage forests and opened lands, capture and retain water, reclaim wetlands, sustain monumental building projects, and fill the ranks of the military to combat and raid other city-states, all during a time of increasing aridity (111). By the end of the eighth century, the ruling elite were unable to deliver on their social promises, despite their many efforts to do so. Intercity conflict increased (112, 113), perhaps even class conflict (114), creating a synergy that reinforced the myriad problems in their high-cost human–environment system under aridification. The old political and economic structure dominated by semidivine rulers decayed. Peasants, artisan–craftsmen, and others apparently abandoned their homes and cities to find better economic opportunities elsewhere in the Maya area, leading to a significant depopulation, even abandonment, of many major city-states and their hinterlands in the CMLs (115). To date, there is little evidence for large-scale famine and death at the time of this abandonment (95, 116).

Quasiconfirmation of this model of the collapse and depopulation of the CMLs is provided by the dynamics of city-states throughout the Lowland Maya territory (117). To the west of the CMLs, there was a decline at city-states on or near the Usumacinta River, such as Piedras Negras, Yaxchilan, and Palenque (Fig. 1). To the south, some of the city-states on or near the Pasión River, such as Dos Pilas, Aguateca, and Cancuen, declined, whereas there was continued occupation at Altar de Sacrificos until the mid-10th century and a 9th to early 10th century florescence at Ceibal. There also was continued occupation at some city-states situated around the central Petén lakes. The area to the east of the CMLs witnessed a decline of cities but sustained occupation of some, but not all, along key riverine and trade routes, such as Lamanai. To the north, a relatively brief but major florescence occurred at city-states in the Puuc region—a hilly land constituting the northern-most reach of interior uplands of the peninsula. There also was a longer boom at the great northern city-state of Chichén Itzá and a continuous occupation at some centers along the coast. The collapse and depopulation of the CMLs were not experienced similarly among all locales and cities/hinterlands in the CMLs.

This complex picture of collapse/noncollapse and abandonment/continued occupation that occurred under prolonged regional climatic aridification leads us to the inference that local to regional differences in key environmental and socioeconomic factors played important roles in the Classic Maya collapse. Regional variations in the severity of aridification and timing of precipitation may explain some of the collapse–noncollapse outcomes. However, access to water was a necessary but not sufficient condition for noncollapse. Many cities with such access collapsed, such as the humid and water infrastructure-rich city of Palenque (118). There is virtually no evidence that reduced precipitation was countered by use of irrigation, including in the northern Yucatán, which survived the Terminal Classic and remained occupied (Fig. 1).[¶]

This evidence leads us to the inference that socioeconomic factors were at play. These factors include access to riverine/coastal transport, prevalence of intercity conflict, adjacent lands to relieve population pressures, and most importantly, macroeconomic changes involving trade (12, 104, 108). Although all four factors likely played a role in the variability of the bust or boom of city-states and areas in the Lowlands during the ninth century CE, we firmly believe that the current evidence points to the fourth factor as being the most important. Whereas trade always played an important role in the development of ancient Maya civilization and seaborne trade was certainly practiced during Preclassic and Classic times, the latter rose in economic prominence in the Postclassic Period (110). Cities and towns located on the coast or waterways with access to seaborne commerce had obvious advantages in the face of the environmental stresses and challenges at the end of the Classic Period that we have outlined above. Both push and pull factors played a role in the Classic Period collapse and depopulation of the CMLs.

Nonrecovery Postclassic

Part of the mystique of the Classic Period devolution in the CMLs resides in the fact that the forest recovered, but the population has yet to do so. The expanses of this forest cover historically served as a refuge for Maya seeking to escape Spanish and Mexican dominion (119). In the late 19th and early 20th centuries, these forests provided dyewood, latex, and tropical hardwood (120). Today, the density of occupation of what was the CMLs remains about one to two orders of magnitude less than the density of the Late Classic Period, depending on the location in question (13, 70). The region remains one of the few large areas of the world that has exhibited only one millennium-long wave of occupation growth and decline (121). What insight does this postcollapse history provide about the collapse?

First, whatever the degree of land degradation and aridity that prevailed in the CMLs at the time of the collapse, it took only 80–260 y for the region to be dominated again by old-growth forests and 120–280 y for soil to stabilize (54). How long it took the canopy to rebuild soil phosphorus is not known. Regardless, the paleorecord indicates minimal, if any, significant subsequent human disturbance to the forests or soils until current times, except for selective logging as noted above. The forest registered a return to more humid conditions, but its species composition was apparently altered by past Maya uses in at least two ways: by the prevalence of economically useful species, perhaps the relics of Maya orchard gardens and managed forests (93, 122), and by large stands of ramón (*Brosimum alicastrum*), a species with edaphic preferences for the conditions found in disturbed soils, foremost the ubiquitous surface limestone rendered by ancient Maya construction (123).

Given that environmental conditions more or less recovered to those conditions encountered at initial Maya occupation, why were the CMLs and other large parts of the Lowland Maya realm not substantially reoccupied? Cortes' expedition (1524–1526) from Mexico to Honduras almost did not make it through the region owing to the paucity of pathways through the forest and villages for supplies, and it was saved only by stumbling on the Itzá people, who lived around the central lakes of Petén, northern Guatemala (124). The answer likely entails the absence of sufficient land pressures or commercial advantages to warrant reentering the interior uplands, let alone the high costs of clearing the forests and rebuilding the infrastructure for substantial occupation. This answer is consistent with the overall diminution of CML population more broadly and the sustained economy of commerce around the peninsula, rather than across it, throughout the Postclassic Period and other historic periods. In essence, the return of environmental conditions, relatively similar to those conditions in which the Maya originally encountered, was not sufficient to warrant reoccupation of the CMLs. The population and commercial shifts that followed the Classic Period collapse remained in place, reified by Spanish colonization of the Yucatán and its impact on the Maya population (125).

Conclusions

Distant past and data-sparse human–environment relationships are ripe for simplification, especially those relationships emphasizing one or two exogenous factors as the cause of socioeconomic, political, or cultural transformations. The availability of written records that match the paleoenvironmental and archeological data in time and place invariably challenges simplifications, illuminating the complexity of human–environment systems and the role of societal choices (8, 10). Such complexity, however, neither denies the role of exogenous factors in precipitating events nor renders systemwide generalizations moot or not useful. Balance between the extremes of generalization and context is required (10). Identifiable general processes are invariably at play in socioenvironmental systems, affecting complex system dimensions: in the CML case, trends and trajectories, legacies, and thresholds were affected (10). The consequences for either the human or environmental subsystem, however, are also shaped by the properties (context) specific to the case. This realization is a foundation for sustainability science (126).

Understanding the Classic Period collapse and depopulation of the CMLs requires this balance. Climate change, specifically aridity, was an important exogenous forcing on human–environment conditions throughout the Maya Lowlands during the Late Classic Period. The paleorecord is increasingly unequivocal on this point, and the strength of the evidence overrides mid-20th century interpretive resistance to it. This same record,

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[¶] It is noteworthy that the northern Yucatán, on average, is the most climatically arid part of the Maya realm, even with the return to more humid Postclassic conditions. Aquifers may be reached there for potable water, and in some locations, the water table is shallow. No evidence exists, however, that the aquifers were used for irrigation, and no evidence informs us of any cultivation practices that tapped the shallow water tables. At least one study, however, suggests that northern wetlands may have been used for some sort of recessional cultivation (82). Indeed, seasonally inundated lands may have been used more throughout the CMLs as aridity increased (79) and in some cases, into the Postclassic.

however, indicates that endogenous factors were equally important within the CMLs, and foremost was the scale of landscape changes and resource stresses generated by its occupants that amplified climatic aridity and its environmental impacts. This amplification was likely much larger than the amplification experienced during previous drought episodes from which the CMLs had recovered.

Something else was at play, however, indicated by those areas and city-states throughout the Lowlands that persisted and even flourished beyond the Terminal Classic Period. Access to rivers, lakes, aquifers, and other sources of fresh water is insufficient to explain these cases. Also, why did the Maya never reclaim the Classic Period heartland after its environmental recovery? The answers likely reside in the overland to coastal shift in commerce that undercut the economy of the CMLs and the overall lowering of the Postclassic Maya population that simply did not have to expand its land base back into the interior uplands.

Surely, this picture is incomplete, but it returns us to the collapse theme proposed 40 y ago (15, 20) before current attention to vulnerability, resilience, complex adaptive systems, and sustainability. Complex system interactions generated the collapse and depopulation of the CMLs and fostered its long-term abandonment. This lesson—increasingly voiced in the literature (15, 21)—should be heeded in the use of analogs for sustainability science.

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