LESSONS FROM THE MAYA*

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In 1977 concern for the long-range effects of policy-making prompted President Carter to direct the U.S. Council on Environmental Quality and the Department of State to study the "probable changes in the world's population, natural resources, and environment through the end of the century." The projections of that commission, as detailed in *The Global 2000 Report to the President* (Barney et al. 1981), foresee a growth in the world's population of as much as 70 percent, combined with staggering increases in demand for the world's resources of water, minerals, soils, and forest products. The report concludes that

> the most serious environmental development will be an accelerating deterioration and loss of the resources essential for agriculture. This overall development includes soil erosion; loss of nutrients and compaction of soils; increasing salinization of both irrigated land and water used for irrigation; loss of high-quality cropland to urban development; . . . extinction of local and wild crop strains needed by plant breeders for improving cultivated varieties; and more frequent and more severe regional water shortages—especially. . . where forest losses are heavy and the earth can no longer absorb, store, and regulate the discharge of water. (P. 32)

This sobering assessment underscores the serious implications of present trends for the future quality of the world environment. At the same time, it dramatically highlights the intricate balance between human exploitation of resources and the cycles and processes of natural ecosystems. Nowhere is the precariousness of this situation more evident than in tropical lowland forests.

More than one-half of the world's "closed" or mature forests, which comprise over seven hundred million hectares worldwide, are located in tropic and subtropic regions, and they are being rapidly cleared for farmland, fuel, and economic development (Persson 1974; UNESCO 1978). In Latin America, where closed forest occupies approximately one-third of the total land area, deforestation is proceeding at rates as high as 4 percent per year. It is projected that the great tropical

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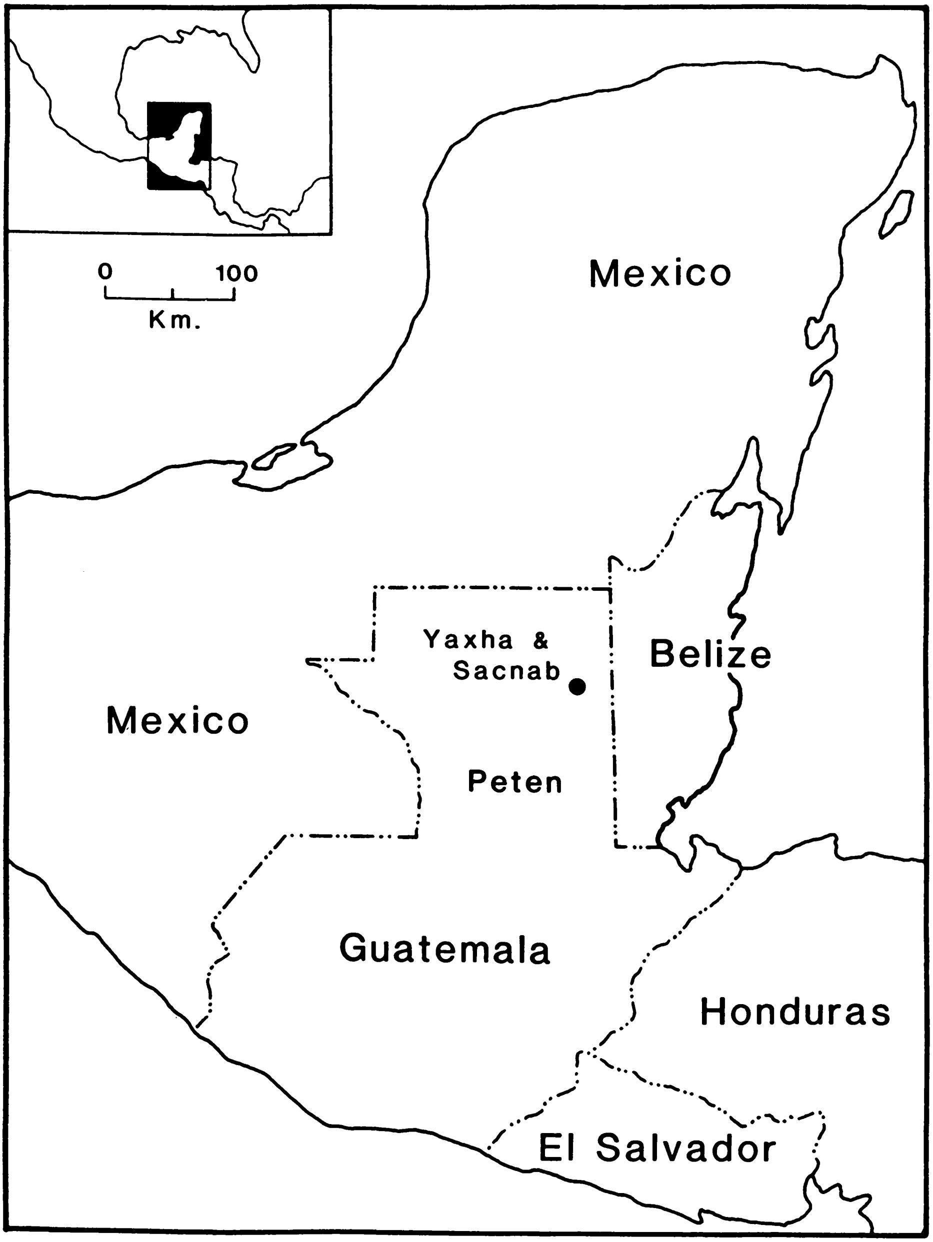
moist forest of the Amazon will cover less than one-half of its present area by the year A.D. 2000 (Barney et al. 1981, 127).

Agriculture, ranching, lumbering, and community expansion are moving tropical forests to the brink of wholesale destruction through the removal of trees. But the problem of uncontrolled modern extractive development of tropical forests is far more complex than this simple statement would suggest. Its real significance may be appreciated only through considering some of the biological characteristics of tropical forests, especially as they are distinguished from temperate forests. The distinctions hinge on the structure of the productivity of a forest ecosystem, which is a function of mineral storage, nutrient cycling, and biomass. The essential components are soil and standing vegetation, and in tropical forests, these components are in a fragile and delicate balance.

In a forest of temperate regions, the soil contains the major proportion of nutrients to sustain production and growth. When a temperate forest is cut, the soil retains most of those nutrients and stores them until they are extracted by forest regeneration or agriculture (Odum 1971, 102–3). Temperate forest regeneration is slow, however, taking as much as one hundred years to reach maximum biomass (Farnworth and Golley 1974, 76).

In tropical forests, by contrast, the vegetation cover, rather than the soil, holds the key to overall productivity. Tropical lowland forests are characterized by extremely high biomass and rapid rates of nutrient cycling (Richards 1952; Stark 1971; UNESCO 1978). More than 75 percent of the nutrients in the ecosystem are tied up in living vegetation and dead organic matter on the forest floor (Golley 1975; Whittaker and Likens 1975). Under the high heat and rainfall conditions of the tropics, the dead forest litter rapidly decomposes and is quickly recycled into vegetation growth rather than enriching the soil. Recent agronomic research indicates that tropical soils are highly variable in their nutrient status and can be quite fertile (Sánchez and Buol 1975), but because of the high ambient temperatures, heavy precipitation, and the thinness of the soils, they do not store nutrients as effectively as do temperate forest soils. Most nutrients in tropical forest soils are contained in the upper thirty centimeters of the profile, and correspondingly, it is here that 65 to 80 percent of the forest vegetation's root system is also found (Greenland and Kowal 1960).

When treefalls or limited clearings are created in tropical forests, vegetation can quickly reestablish itself; the forest rapidly accumulates nutrients from the soil and has the capacity to attain as much as 90 percent of its total original biomass in ten years or less (Sánchez 1976, 351). If a large section of the forest is cut and burned, however, as is typical in clearing operations for agriculture or settlement in tropical regions, nutrients are immediately released to the soil in the absence of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vegetation to recapture them. Expanses of unprotected soils subsequently are exposed to heavy rainfall, with consequent deterioration of the soil structure, erosion, and the leaching of soluble nutrients deeper into the subsoils beyond the effective reach of crops or vegetation. Prolonged or repeated exposure dramatically accelerates alteration of the soil matrix and the hydrological regime, further diminishing the already restricted capacity of the ecosystem to store and cycle nutrients. In these situations, the process of regrowth and recovery after forest clearance is a long and slow one. Ultimately, the consequences of extractive exploitation of tropical forests are not only soil erosion, destabilization of water flows, and nutrient loss, but elimination of a fabulously rich capital resource in the form of stored photosynthetic energy and biological diversity.

The Global 2000 Report acknowledges that at present there are no successful methods by which to analyze the balance between the benefits and these relative costs of transforming tropical forest land to other uses (Barney et al. 1981, 132). The failure of resource planners for tropical regions to develop long-range strategies for present and future use of tropical forests that would prevent such losses is linked in part to the inability to evaluate the long-term impact of human exploitation of tropical forests until irreversible damage already has occurred. Unfortunately, few modern societies can serve as models for such assessments because they have replaced forests after clearance and do not continue to use them.

This lack of foresight—an inability to translate from the present to the future—that underlies rampant consumption is matched by a concomitant failure of hindsight—an inability to learn from the past. Large, wasteful, and exploitive populations are not exclusively modern phenomena: cities and civilizations have come and gone for millenia, and in their histories lie many lessons as to the nature of this uneasy balance between society and environment. Ancient civilizations in theory could provide a long time span for investigating human impact on tropical environments, but most ancient civilizations—Sumer, Egypt, Teotihuacan, Mohenjo-Daro—arose in arid valleys, rather than in lowland forests. Rarely did an ancient civilization call a tropical forest "home." Instead, tropical forests seem to have been viewed in both the past and the present as impenetrable "jungles" of strangling vegetation, with a reputation for limited agricultural potential and a concomitantly retarded cultural development (Meggers 1954).

At least one ancient civilization belies this view. The Maya civilization arose in the lowland tropical forests of Belize, Guatemala, and Mexico, where it flourished from approximately 1000 B.C. to A.D. 1525. During the period from A.D. 300 to 900, the Maya attained what is considered to have been a pinnacle of "Classic" development (Culbert 1974). Their superlative achievements are known to archaeologists through their architecture, art, and artifacts, which include huge temple pyramids, sumptuous burials, carved stone monuments, painted pottery, murals, and trade in exotic goods. These and other lines of evidence illuminate the Classic Maya as a hierarchically organized, theocratic society with an agricultural base, a complex calendrical system, elaborate ceremonial and religious activities, and a powerful political and economic leadership.

In the ninth century, the Maya star began to wane over much of the lowland region. The rapid cultural decline and population loss that is thought to have occurred is referred to by archaeologists as the "collapse" of the Classic Maya (Culbert 1973). The causes for this decline have puzzled archaeologists for decades, and such factors as malnutrition, disease, foreign invasion, and internal civil uprising have been suggested as possible explanations. Other hypotheses concern the relationship of the Maya to their environment, positing soil exhaustion, crop failure, and famine as underlying causes of the "collapse." The basis of the whole Maya agricultural system as well as the methods by which the society sustained itself agriculturally up to the ninth century are being increasingly investigated (Flannery 1982; Harrison and Turner 1978), and they raise nagging questions about the long-term interactions between a complex society and its fragile lowland forest environment. Mayanists long have been interested in the question of the relevance of the Classic Maya "collapse" to modern society (Sabloff 1971) because these questions surpass mere academic interest, given the modern threat to the remaining reserves of tropical forest.

THE CENTRAL PETÉN HISTORICAL ECOLOGY PROJECT

In order to understand better these interactions between society and environment through time, a continuing historical ecology research project was initiated in Guatemala in 1972. The location chosen for this study was the Department of Petén in northern Guatemala, the heartland of Lowland Maya cultural development. By means of geochemical, biological, and archaeological studies, this project set out to investigate the effect of Maya occupation on a tropical forest ecosystem.

The investigation was structured around an unusual research perspective. In many sciences, including ecology and archaeology, research often must proceed without the controlled laboratory experimentation that characterizes other sciences such as physics or chemistry. Large environmental and social systems are not usually amenable to experimental manipulation; instead, the situations already provided by time and history must be viewed by the scientist as the "experiments." In such cases, the objectives of the research are to define the "experimental conditions" within which the events of history took place (Deevey 1969).

From this perspective, the Maya provide a laboratory for the study of long-term environmental impact and resource management. The two thousand years of development of Classic Maya civilization in Petén can be regarded as one of the few large-scale "experiments" in the use of tropical forest by a complex society. The conditions of that experiment—that is, its cultural and environmental parameters—are largely unknown to scholars, however, which is the reason why the outcome—the collapse and its causes—are still being debated.

Among other considerations, the debate concerns the degree to which this agricultural society may have affected its environment adversely so as to undermine subsistence productivity and contribute to its own decline. In the terms of our research project, if the Maya did severely alter the forest ecosystem, the strain should be identifiable both demographically (by measurement of human population dynamics) and through paleoenvironmental characterization (including evidence of vegetation history, hydrological relations, soil integrity, and nutrient cycling).

The thirty-six thousand square kilometers of lowland forests of the Department of Petén constitute modern Guatemala's last reserve of virtually uninhabited land. The area has been underpopulated since the decline in the ninth and tenth centuries of the Classic Maya populace, which is estimated to have numbered in the millions (Adams, Brown, and Culbert 1981). This condition of sparse settlement is rapidly ending, however. The Petén is currently experiencing a flow of new farmers and ranchers from the heavily populated highlands to the south, a movement stimulated by recent governmental land-granting policies. Rapid in-migration has pushed the Petén's population from a level of 25,910 inhabitants in 1964 to almost 200,000 by the close of the 1970s (Castellanos López 1980; Schwartz 1977).

Upon arriving, migrants have cleared the forests to make room for economic development in the form of cornfields, cattle ranches, and lumbering for export. The scale of the transformation lends credence to the observation that in Central America, closed forests "are diminishing at about 2 percent per year and are likely to be completely removed from arable areas by the year A.D. 2000" (Barney et al. 1981, 127). The newcomers have chosen to settle primarily along modern roads and rivers and on the elevated terrain that supports high forest. Here the combination of variability in microtopography, soils, and vegetation makes for considerable differences in food production capability, thus contradicting the common, but erroneous, view of lowland tropical forests as ecologically homogeneous.

The Petén environment actually is decidedly heterogeneous, at least in terms of the factors influencing productivity—availability of water, topographic relief, soil drainage and fertility, and forest composition. The compositional diversity of Petén's forests is broadly sensitive to a north-south rainfall gradient (2000 millimeters annually in the north, over 3000 millimeters in the south), as well as to more localized soil conditions and relief (FAO 1970; D. Rice 1977; Simmons, Tarano, and Pinto 1959). Relief is determined by underlying Miocene and Eocene limestones, which have formed a series of karst hills and east-west ridges (West 1964). As in many karst areas (limestone regions characterized by sinks and irregular topography resulting from dissolution of the rock and subsurface drainage), the availability of water is a serious problem in the Petén, where few permanent water sources exist. In addition, the region is drained by few permanent streams. Much of the terrain is occupied by seasonally inundated perched depressions called *bajos*, which are zones of unconfined water existing near ground surface where downward movement is impeded by an underlying stratum of impermeable clays. Bajos are characterized by dense low forest and are recharged during the rainy seasons by precipitation or overland flow from adjacent surfaces.

The relative lack of perennial water sources in Petén is relieved in the central portion of the department, where a chain of lakes formed at the close of the Pleistocene (Deevey, Brenner, and Binford 1983) along an east-west fault fracture roughly coinciding with seventeen degrees north latitude. This lake region is significant as a research locale for our investigation of long-term adaptations of an agricultural society to a lowland tropical forest environment.

Human colonization and settlement of terrain frequently have been guided by the water supply, protein resources, and ease of movement afforded by water bodies or by patterns of resources such as soils or vegetation that are organized with respect to the characteristics of drainage basins (Smith 1969). In the central Petén, several lines of evidence reveal that the area sustained continuous human occupation throughout the entire period of Maya prehistory. Pollen recovered from lacustrine (lake) sediments gives the earliest suggestion of agricultural disturbance in Petén, beginning about five thousand years ago (Vaughan 1979). Archaeological and ethnohistoric records indicate that the area experienced continuous settlement up to and after the collapse, then through the Postclassic period to the time of sixteenth- and seventeenth-century Spanish contacts (Jones, Rice, and Rice 1981; D. Rice n.d.; P. Rice n.d.). This long history of occupation in the lakes area has produced a large body of archaeological data—residences and civic-ceremonial structures, plus the spatial distribution of these edifices and associated artifact materials—that can allow estimation of Maya settlement sizes through time.

In addition, the lakes themselves provide information that allows assessment of the effect of these changing Maya populations on their environment. Lakes and their terrestrial surroundings often are considered as distinct systems, but they are inextricably linked by meteorological, geological, and biological processes that transfer materials, nutrients, and energy from one system to the other (Likens and Bormann 1974). Lakes serve as traps or catchments for accumulating sedimentary products of processes taking place in and around their basins. Because lakes are downhill recipients in the relationship, their physical, chemical, and biological processes are profoundly affected by the types and magnitudes of these transfers. In mature terrestrial ecosystems, loss to the aquatic sector is minimized and stabilized by the presence of standing vegetation. When the biological component of the terrestrial system is disturbed, however, transfers to the lake are altered and accelerated.

Paleolimnological study can document past events in a lake and its drainage because changes in the watershed are preserved as a record of alterations within the sediments on the lake bottom. That paleolimnological record, in conjunction with archaeological data or historical information or both, can be used to establish the impact of human activity on a basin, including density of occupation or shifts in land use (Cowgill and Hutchinson 1964; Mikulski 1978; Pennington 1978; Vuorinen 1978). The Petén lakes have a particular advantage in that they are closed, that is, no stream outflow exists, and so they preserve relatively undisturbed evidence of natural and artificial (human-induced) changes in the larger ecosystem. Such evidence includes pollen, carbonized fragments of terrestrial vegetation, mineral and chemical inputs from terrestrial runoff and rainfall, and fossils of animals and plants that lived in the lake waters.

A pair of lakes at the eastern end of the chain, Yaxha and Sacnab, was selected as the location for beginning efforts at correlating Maya population history with natural history. Subsequent archaeological and paleolimnological investigations by our team in the region have studied Lakes Macanche, Salpetén, Quexil, and Petenxil, but we are focusing here on Yaxha and Sacnab to demonstrate the efficacy and results of the approach. The two lakes are separated by a narrow isthmus and differ in size, Yaxha having a shoreline of twenty kilometers and a maximum depth of twenty-seven meters, while Sacnab has a shoreline of twelve kilometers and a maximum depth of thirteen meters. Previous archaeological work suggested that these two lakes diverged in their occupation histories as well (Bullard 1960, 1970). The differences in size and population of the two lakes established the variation within the "experimental parameters" of the historical ecology project: the sediments of each lake could be investigated for conditions before, during, and after

Maya occupation, and the two lakes' sedimentary histories could be compared in terms of the effects of high versus low occupation intensities.

Archaeological Research

The objectives of the archaeological research program were to locate settlement remains in the basins of Lakes Yaxha and Sacnab in order to determine the size and density of human populations in each basin as well as changes in such occupation through time. These determinations allowed comparison of the similarities and differences in settlement between the two lakes, as well as evaluation of the effect of changing human-settlement characteristics on the history of the lacustrine environment. This phase of the research consisted of two steps: the survey and mapping of settlement remains within defined areas and a program of test excavations.

Because it was physically impossible to survey the entire pollen- and sediment-producing area of each lake basin, surveys were restricted to rectangular sampling units (transects) radiating out north and south from the shore of each lake for a distance of two kilometers (the approximate limit of the hydrographic basins). Each transect was searched for structural remains, which were mapped, and then approximately 25 percent of these were excavated by small, one-meter-by-two-meter test-pits. Broken pieces of pottery and stone tools recovered from these excavations allowed estimates of the date of building of the structures because of a peculiar Maya construction practice. Maya builders apparently gathered up available household refuse at the time of construction and mixed this debris with the rubble and dirt that comprised the bulk of the fill of walls and floors. In addition, it was common practice to remodel earlier structures, thus incorporating previous constructions into the new edifice. Centuries later, archaeologists excavating a structure can determine the approximate time or times of construction by the latest pottery styles that are incorporated into one or more rubble fills.

It was known from earlier archaeological work that Lake Yaxha was heavily settled from the Preclassic (1000 B.C.–A.D. 250) through Classic periods (A.D. 250–900) and also in the Postclassic period (A.D. 900–1697) of Maya history in Petén. Lake Sacnab, on the other hand, was more lightly occupied during the Preclassic and Classic periods. Lake Yaxha was further distinguished by the presence of a large Classic period civic-ceremonial center with numerous temples and carved stelae (erect stone monuments that were often sculptured), the site of Yaxha, on its northern shore. Following the collapse, the Yaxha basin saw sizeable Postclassic settlement focused on the Topoxte Islands, located off the southwestern shore of that lake. Lake Sacnab, smaller and to the east, had no comparable large Classic period centers and no Postclassic occupation at all.

The archaeological investigations of the historical ecology project in Petén filled in the details of this broad outline of settlement in the Yaxha-Sacnab basins. The distribution and dates of construction of structures on the Yaxha-Sacnab transects suggest that the basins were first occupied by about 1000 B.C. (P. Rice 1979). Within the sampled zones, early communities in the Middle Preclassic (1000–250 B.C.) and Late Preclassic (250 B.C.–A.D. 250) periods were generally located on the well-drained uplands and may have been oriented around small special-function areas with temples or civic structures and plazas. Initial settlement in our sampled areas was denser around Lake Sacnab than Lake Yaxha, although the latter exhibited a greater number of structures because of its larger basin area. During the Middle Preclassic, several settlement loci on the south shore of Lake Sacnab exhibited monumental architecture, as did the center of Yaxha on the north shore of that lake. By the end of the Late Preclassic period, however, the architectural growth of the site of Yaxha had far exceeded that of others in our transects (D. Rice 1976).

During the following centuries, population increase in the basins necessitated shifts in settlement focus from apparently favored upland terrain to areas that were not as well drained. The uneven distribution of desirable upland terrain around the lakes plus the growth of the site of Yaxha and changes in the sociopolitical fortunes of neighboring sites and areas combined to cause different densities of settlement at the two lakes (Rice and Rice 1980). For example, there were three times as many structures per square kilometer in the Lake Yaxha basin by the Late Classic period (A.D. 500–900) as existed around Lake Sacnab.

Settlement growth peaked in the basins between A.D. 700 and 900 and was followed by a dramatic population loss and change in settlement location. The Sacnab basin remained uninhabited in succeeding centuries, while the Topoxte Islands in Lake Yaxha were occupied as a node of Postclassic residence and civic-ceremonial activity (Rice and Rice n.d.). This Postclassic focus on the islands in Lake Yaxha is part of a broader overall settlement retrenchment to the lake basins of central Petén after the tenth century (D. Rice n.d.; P. Rice n.d.).

The size of Preclassic and Classic occupation in the basins can be shown to have increased approximately exponentially through time. This growth can be demonstrated by means of a demographic curve, which is constructed from the combined survey strip-settlement figures by plotting the maximum number of structures built or occupied during each phase as an end-of-phase estimate of population size. In so doing, we assume that by the end of each phase, the structures constructed during the phase were contemporaneous (Haviland 1970, 191). Although the chronological intervals are rather coarse and the dynamics of growth within any period, or from one period to the next, are likely to have been highly variable, the slope of the line indicating log-linear growth suggests a growth rate on the order of 0.17 percent per year, or a doubling time of 408 years.

The settlement growth curve for structures can be converted to a population profile by a formula in which the total number of structures per phase is adjusted to reflect the actual number of residences, and the resulting figure then is multiplied by an estimated constant population per residence (D. Rice 1978, 42–46). In computing population figures, it was assumed that approximately 84 percent of the total number of structures occupied during a phase were actual residences (Haviland 1970, 193) and that 5.4 persons per structure is a stable average for Preclassic and Classic population estimates (Puleston 1973, 183). Although it is doubtful that these constants were invariant from area to area or through time, they do allow us to propose an approximate magnitude of population density per square kilometer within the basins, per time period. Such a conversion adds no new information on the rate of demographic change, but these population estimates become significant for estimating the approximate per capita impact of exponential growth within the lacustrine ecosystem.

From an average of 25 persons per square kilometer by the close of the Middle Preclassic period, the population in the Yaxha-Sacnab basins rose to an average of 211 persons per square kilometer in the Late Classic. Population sizes and densities are more difficult to project for Postclassic populations, whose residences were apparently largely confined to the site of Topoxte. Between 750 and 1000 people may have lived on the island we sampled (the second largest of the four "island" loci of Topoxte), but Postclassic densities for the entire Yaxha-Sacnab basins would have been low, perhaps as low as Middle Preclassic levels. Although fluctuations of population cannot be identified over short periods of time, the overall Preclassic-to-Classic demographic trend suggests no factors limiting growth until the end of the Late Classic period (the collapse), or at least no constraints that could not be overcome by technological or social means. Nonetheless, the continued growth of agrarian population in the basins during the two thousand years of Maya occupation preceding the collapse undoubtedly had some effect on the environment. The paleoecological aspect of the historical ecology project was designed to measure that impact.

Paleolimnological Research

Because lakes act as traps for erosional materials and for nutrients and chemical elements being cycled by the terrestrial plants and animals within the system, they are excellent indicators of human activities in their watershed. Forest clearance for agriculture and architectural construction is a major source of such disturbance. Deforestation, establishment of agricultural crops, field abandonment, and natural succession, for example, are all reflected in the kinds and amounts of pollen that find their way into the lakes. As landscape is put into production for long periods of time, protracted manipulation and exposure contribute to structural degeneration of the soil and altered local water flow, the products of which ultimately find their way to the lake sediments.

Soils under vegetation cover are relatively deep, benefiting from the buildup of an organic-rich horizon with open structure and good permeability. By breaking the impact of raindrops on the soil surface, vegetation permits more gradual interception of rainfall by the soil; surface depressions fill and infiltration of water into the subsoils begins apace. This infiltration contributes to soil moisture storage and deep percolation of water to saturated zones of ground water, as well as to downhill water flow *within* soil layers (called "throughflow"), where the permeability of those layers decreases with depth (Chorley 1969). Where rainfall intensities exceed infiltration rates, overland flow or runoff of rainwater occurs, which moves much more rapidly and differs physically from the throughflow moving through subsurface soil pores. Within basins of well-structured soils under mature forest, runoff is minimized and tends to occur uniformly throughout the basin (Kirkby 1969).

The contribution of standing vegetation to soil structure and to the amount of rainfall intercepted depends on the types of plants and their stage of growth. Prolonged deflection of forest to crop plants, successional species, or exposed earth leads to breakdown of soil structure, soil compaction, increased impermeability of the soil surface, and reduced infiltration. These conditions contribute to increased overland flow at the expense of soil moisture and ground water recharge as well as to throughflow. The heightened volumes and velocities of runoff accelerate erosion of the products of structural deterioration of soil. Under corn plants, for example, which are relatively poor at holding soil, gently sloping terrain can lose around twenty tons of soil per acre per year (Barney et al. 1981, 281).

Physical manipulation of the landscape surface, such as in cropping and construction activities, further exaggerates erosion and waterborne transport of soils (slopewash). Mechanical breakdown or removal of soils decreases the contextual integrity of surfacial organic and inorganic materials, while the covering of the landscape with impervious architectural surfaces further increases the rates of removal and downhill deposition of those materials. In lake basins, these terrestrial outputs eventually enter the aquatic zone, altering the chemistry of lake waters and influencing the kinds and growth characteristics of aquatic flora and fauna. There they become incorporated into the accumulating lacustrine sediments, forming a stratified record of the natural and cultural history of the catchment.

A major portion of the ecological research program in the Yaxha-Sacnab basin was a paleolimnological study that was undertaken to recover quantitative evidence of the sequence of sedimentary, palynological, chemical, and microzoological and microbotanical inputs into the lakes. The sediments were sampled for study by drilling into the floor of the lakes to remove a column or core of the sequentially deposited sediment layers. A core 7.4 meters in length was obtained with a Livingstone piston-corer from Lake Yaxha in 1973, and a core 6.4 meters in length was extracted from Lake Sacnab in 1974. The cores were transported to the Florida State Museum, where they were extruded, described, and sampled for pollen, chemical composition, aquatic fossils, and organic materials suitable for radiocarbon dating.

The major constituent of the sediments of both lakes was found to be a thick layer of silty montmorillonite clay, with increasing proportions of limestone inclusions in the upper reaches of the cores. This layer is an erosional deposit of sediments moved downhill by gravity (colluvium) or by water (slopewash) as a result of Maya disturbance. Above this "Maya clay" deposit lies an organic layer corresponding to the last few centuries of modern, post-Maya occupation. The heavy clay in Lake Sacnab was underlain by a pre-Maya layer of similar, highly organic mud. In Lake Yaxha, the clay sediments were so thick that the coring apparatus could not penetrate below the section into the pre-Maya layer.

The gross stratigraphy of the two cores reflects sedimentation resulting from Maya disturbance, with amounts of deposition keyed to relative amounts of human activity in the basins. More detailed analysis, however, depends on establishing rates of sedimentation as measured on a temporal scale that can be correlated with the events of Maya history. Because shifts in the composition of sediments indicate changing erosional processes within the basins, the organic-inorganic transition interfaces are thought to be reliable markers of the onset and termination of Maya occupation in the catchments. The organic zones indicate the deposition to lake sediments of remains of largely internal (autochthonous) origin, that is, aquatic plants and animals, while the inorganic zone reflects dramatic terrestrial disturbance.

Pollen deposited in the sediments of Lakes Yaxha and Sacnab, as well as in other lakes of the chain that were studied as part of the project, demonstrate a comparable sequencing of broad zones of species composition (Deevey, Garrett-Jones, and Vaughan 1980; Vaughan 1979). This sequencing permits relative dating of the sediment layers corresponding to the periods of Maya occupation and is anchored by an early radiocarbon date, circa 6500 B.C. (uncorrected), from one of the lakes (Quexil) lying to the southwest (DAL 198, 8410 ± 180; Ogden and Hart 1977).

Chronological zoning of the cores involved the assignment of archaeological dates to various sediment levels within the inorganic layer based on the identification of discrete pollen assemblages. The basic assumption of this procedure is that the degree of deforestation reflected in the regional pollen profiles will track population densities projected from the archaeological data. The resulting temporal sequence for the section of "Maya clay" commences with a progressive decline of arboreal or high-forest pollen from Preclassic through Classic periods. Accompanying this decline is an increase in the weedy or "disturbance" species associated with human agricultural activity and forest clearance. An interruption in this trend—a decline in cultivation weeds and an indication of reforestation—is correlated with the Classic Maya collapse (Vaughan, Deevey, and Garrett-Jones n.d.). Subsequent increases in grasses and decline in arboreal pollen reflect Postclassic Maya activity in the basin, which is followed by a rise in successional species and modern reforestation (Vaughan 1979).

The correlation of pollen zones with archaeological periods of Maya prehistory links a relative environmental stratigraphy to absolute time. This step permits evaluation of relative rates of chemical inputs to the lakes during these periods as indicators of human impact on the lacustrine environment. In determining the effect of growth of Maya settlement in the basins, we are particularly interested in two elements, silicon and phosphorus. Unlike other elements critical to plant growth (such as carbon, nitrogen, or sulfur), silicon and phosphorus lack atmospheric components to their biogeochemical cycles. Their net flow is unidirectional to the lakes and their rates of delivery to lacustrine sediments reflect their rates of extraction and movement within the basins.

As silica (SiO_2, quartz) or as alumino-silicate clay minerals, silicon is important as the main constituent of soil. Most silicates in lake sediments were originally terrestrial soils, transported and redeposited from shores as mineral fragments (clastics), and their accumulations reflect the impact of architecture and agricultural engineering on the environment.

The high rate of silica deposition in Lakes Yaxha and Sacnab is signalled by the thick montmorillonite clay sediments corresponding to the period of Maya occupation. The differential thickness of these clay layers in the two basins reflects the relative degree of human disturbance on their shores. Lake Yaxha, which was more heavily settled and experienced more intense engineering activities, has a clay deposit more than one meter thicker than that of Lake Sacnab, despite the fact that the Yaxha core is an incomplete sample of the Maya period sediments. In both lakes, the quantity of clay deposition was such that to this day, the waters of the lakes continue to be effectively sealed or insulated from ground waters.

Phosphorus, on the other hand, is a biological element that is geochemically scarce but essential to support life in all ecosystems. Phosphate ions are made available to plants through the slow process of the weathering of rock during soil formation, and they are not abundant in the geological materials of limestone regions such as Petén. In addition, phosphate ions are highly reactive with other chemicals and may become incorporated into insoluble compounds in sediments if not taken up as nutrients by plants. Because phosphorus is limited in the Petén environment and because tropical forests are rapid converters of soluble nutrients, the movement of phosphorus at levels above normal minimums results primarily from human deflection of the element to surface soils through deforestation, sewage and waste disposal, the use of fertilizers, and interments. Thus, phosphorus, like silicon, is a direct indicator of human activity on the lakeshore, and its rate of deposition is a measure of environmental impact.

Inputs of phosphorus into the lakes, like those of silica, rise through the time of Maya occupation, increasing nearly exponentially. In Lake Sacnab, the influx peaks in the Early Classic period and then declines; in Lake Yaxha, the rate climbs from Preclassic through Classic periods and into the Postclassic before declining after the time of final abandonment of the basin (Brenner 1978). High correlations between rates of delivery of silica and phosphorus suggest that both are derived from outside the lake (allochthonous) and that the latter was deposited as an insoluble component of the particulate sediments, rather than the "throughflow" of soluble phosphate ions (Deevey et al. 1979, 303).

MAYA IMPACT ON THE LACUSTRINE ENVIRONMENT

It appears that Maya architectural and agro-engineering activities released phosphorus from vegetation and concentrated it in surface soils. This process involved the direct release of phosphorus to soils through clearing and burning as well as the intermediate cycling in which humans consume plant tissues, utilize the captured phosphorus in their organic processes, then cast off excess or incorporated phosphorus through excretion and death. Much of the released phosphorus was locked in insoluble compounds by limestone-derived soils and removed from the terrestrial environment through erosion, then buried in lake sediments. There it was made permanently unavailable in any form to support forest growth, crops, or human populations (Deevey and Rice 1980). Because bulk transport of soil was apparently the mechanism by which phosphorus reached the lakes, it is impossible to determine the actual percentage of phosphorus that was physically cycled through human bodies.

The inference of phosphorus fixation, translocation, and loss is supported by the results of terrestrial soil testing within the Petén lake basins. Soil profiles sampled in excavations of residence structures or those sampled in the vicinity of Maya construction exhibited extremely high levels of phosphorus, suggesting a human-induced source for the nutrient in these enriched soils (Brenner 1983a). The concentration of phosphorus in surfacial soils, in contrast to the homogeneous distribution of highly soluble sodium or potassium throughout the soil profiles, argues against mobilization of phosphorus and rapid leaching. Rather, continued high influxes of phosphorus (alone among the soluble elements) to post-Maya lacustrine sediments, during a period when nutrient loss should have been diminished by forest regrowth, suggest that sediment and phosphorus entered the lakes together as erosional sediments.

It is significant that the increases in the rates of deposition of these elements are strongly correlated with the rates of human population growth within the basins, although the deposition of silica is more accelerated than that of phosphorus. During the time of Maya occupation of the lake region, silica influxes rose by two orders of magnitude in Lake Sacnab and close to three orders of magnitude in Lake Yaxha. Land areas within the basins apparently were altered at rates so closely correlated with population densities that disturbance is adequately indexed by population size. Settlement distributions and densities suggest that forest clearing and construction may have been the primary forces of change on the steep upland terrain of the basins. Forest was cut and increasing amounts of soil were disturbed or covered over by architectural construction, so as to accelerate erosion. Agriculture has the similar geophysical effect of increasing soil degradation, but unfortunately, we cannot distinguish from the sediments alone the differential impact of architecture and agriculture. Agricultural systems on the southern shores of both lakes, although unconfirmed by ground survey (Adams 1980, fig. 2), certainly would have increased erosion in the lower areas of the catchment.

Over the long term, agriculture and human consumption of botanical products, as opposed to architecture, were the activities that modified the quantities and the rates of mobilization and flow of phosphorus within the system. Phosphorus influxes, like settlement densities, increase in the combined basins by an order of magnitude by the Late Classic period. The significance of the parallel is dramatic: if quantities of phosphorus delivered to sediments are largely of human origin, then population size is not simply an indicator of influx rate but its cause. Because phosphorus is a nutrient, first for plants and then for humans, the linear relationship between population growth and phosphorus loading could be expected—agricultural production, ingestion, excretion, mortality and decomposition, and downhill movement were in long-term balance. In the absence of significant imports of phosphorus into the basins as food crops or botanical products, nutrient loss (sequestering in the sediments) would have progressively reduced available phosphorus within the lacustrine ecosystem because the genesis of phosphorus through weathering in the catchment was proceeding at much slower rates.

Comparing calculated per capita rates of phosphorus output of the populations of these lakes with similar data from other areas allows preliminary evaluation of the impact of human populations on aquatic productivity. In Lake Yaxha, the Late Classic and Postclassic phosphorus delivery of more than fourteen hundred grams per capita approaches a rate that would threaten comparable lakes in temperate climates (Vollenweider 1968; Wetzel 1975, 215–45). Unfortunately, no data are available for long-term effects of such rates of input into tropical lakes. The threat wielded by high levels of phosphorus input is that of "too much of a good thing." The support capability, or biological productivity, of lakes is normally attuned to tiny supplies of phosphorus. Even small, culturally induced inputs of phosphorus can unbalance production dangerously, causing a form of pollution that is referred to as "cultural eutrophication" (Likens 1972). The accelerated input of nutrients such as phosphorus leads to increased growth rates of algae, plants, and animals, which in the advanced stages can cause oxygen to be depleted, anaerobic conditions to be created, and aquatic communities to be altered drastically.

Although we can document accelerated inputs of phosphorus to lake sediments as a result of Maya occupation, we cannot find clear evidence of eutrophication. Attempts to correlate enhanced lake productivity with phosphorus delivery through measurement of organic carbon and analyses of microfossil accumulation have been equivocal. Organic carbon fails to follow a discernible pattern of growth or decline in the lake cores. Similarly, microscopic examination of microfossils suggests that concentrations do not parallel phosphorus deposition, although post-depositional destruction of their remains may have obscured the relationship (Deevey, Vaughan, and Deevey 1977; Brenner 1978, 1983a).

Several factors lead us to believe that the productivity of Lakes Yaxha and Sacnab may have declined progressively during the Maya periods. For one, disturbance-zone sediments in the lakes are highly inorganic and their constituents do not indicate that the episode of deforestation was accompanied by internal organic production. For another, the lake waters were probably made turbid frequently by the inflow of erosional silt; lower rates of biological productivity may be attributable to reduced penetration of sunlight as an energy source for photosynthesis.

Finally, if the major source of phosphorus in lacustrine sediments was soil deposited by slopewash, the element would have entered in the form of insoluble compounds, thus being unavailable as a nutrient to contribute to growth, and it would have bypassed biota during deposition in the lake. This nutrient sequestering, together with the light-reducing effects of siltation, would have retarded cultural eutrophication of the lakes, just as it would have had a negative impact on terrestrial productivity.

Lacustrine changes have their origin in the terrestrial component of the forest-lake ecosystem, and the environmental strain of the growing Maya settlement would have been felt there even more directly. The pollen sequence reflects a progressive deforestation of the region, while accelerated removal of soils and deposition of erosional sediments indicate technological manipulation of the basin surfaces. These modifications would have diminished natural habitats and affected terrestrial resources for the hunting or collecting of wild food supplements, as well as for the collection of botanical resources for construction, crafts, and particularly fuel. The latter strain is often underestimated; approximately one-third of the modern world's population uses wood for fuel, with the average user consuming about one ton of wood per year (Lawless 1978, citing United Nations 1967). The Maya consumption rate was probably comparable.

Moreover, increasing amounts of terrain were being covered by buildings and plazas, which effectively removed some of the well-drained lands from production, in addition to altering local hydrology and promoting erosion. Maya farmers in the Yaxha and Sacnab basins thus had to cope with declining access to upland soils, progressive deterioration of the structure of those available, destabilization of water flows and storages, and constant diminution of essential nutrients within the system.

LESSONS FROM THE MAYA

The Maya, like other large developing societies, made increasing demands upon their environment in order to feed, shelter, and otherwise support their growing populations. It is clear from the Yaxha-Sacnab data that, in this area at least, the Maya drastically altered the terrestrial and aquatic components of their tropical forest ecosystem. Deforestation, agricultural cultivation, and urban construction are known to enhance erosion rates by one, two to three, and three to four orders of magnitude respectively (Deevey and Rice 1980); and the Yaxha-Sacnab data follow a similar trend. Compounding the strain is the related phenomenon of "nutrient sequestering," a process that results in essential nutrients being permanently removed from the terrestrial system. Information from other Petén lakes (Cowgill and Hutchinson 1966a; Binford 1983; Brenner 1983b; Deevey, Brenner, and Binford 1983); other areas of Petén (Cowgill and Hutchinson 1966b; Olson 1969; Olson and Puleston 1972; Wiseman, cited in Turner and Miksicek 1981), and nearby Belize (Wiseman 1982, 1983) suggests the degradation was similar and regional in scope.

The measurement of such alterations confirms the concerns and projections of *The Global 2000 Report to the President*, identifies the processes involved, and provides preliminary estimates of critical rates of change in essential components of the ecosystem. There is more to be gleaned from the outcome of the Maya "experiment" than verification of the fragility of tropical environments, however. The Maya were conspicuously successful in harnessing the productivity of such a landscape for two millenia, and the details of that adaptation constitute positive lessons to be learned for future tropical forest exploitation.

Tropical forests are diverse—in their topography, soil characteristics, and hydrology. As a result, numerous exploitive responses are possible. The Maya of Yaxha-Sacnab functioned within a broader pan-Maya community, and it is on this regional level that the varied strategies of adaptation to the tropical-forest zone become apparent. Both explicit and implicit evidence exists showing that the Maya were aware of the heterogeneity and fragility of their environment and of the impact of their practices on the inherent processes and productivity of the exploited terrain. This recognition is reflected in direct evidence of sophisticated agro-technologies throughout the Maya area, which include terraces (Healy, Van Waarden, and Anderson 1980; D. Rice 1982; Turner 1974, 1979) and systems of raised fields and canals (Adams 1980; Adams, Brown, and Culbert 1981; Siemens and Puleston 1972; Turner and Harrison 1981). The locations of these relic agricultural features indicate effective use of a number of different microhabitats, while their structure, contents, and ecological contexts suggest specific cropping procedures instituted as conservation measures within these varied loci.

Terraces are prominent on upland terrain and gradual planations of exterior drainage, where they check the downhill movement of materials and water. In so doing, they impede the effects of erosion and chemical weathering and build up thick soils. In addition, soils containing fixed phosphorus are held in situ, rather than being lost from the cropping area, and thus allow the slow release of phosphorus ions from insoluble compounds to soil solution over a period of years. In this manner, terracing prolongs the viability of arable land through preservation of soil structure and nutrient content and increases the actual quantity of land that can be considered arable.

Like agricultural terraces, canal-field systems allow for expansion of the cropping area by incorporating inundated zones, such as depressions of internal drainage (bajos) and lacustrine or riverine locations. In these zones, which are not encumbered by architecture and not contested by urbanization, the canal-field constructions provide an improved soil medium for cultivation in which waterlogged soils are essentially recycled. That is, intact soils are either drained through channelization or dug and piled onto a platform to enhance drainage, with water relegated to the resultant adjacent canals. The plots may extend out from the higher ground of depression edges, lakeshores, or river banks, or they may be situated toward the centers of swampy zones with fluctuating, perched water tables. The variability in field construction and placement reflects an understanding of seasonal variability in moisture regimes and the likelihood of scheduling more than one crop per year. Wet-season cropping is feasible on the higher and drier raised fields, while dry-season crops may be sown in the higher canals and on the raised fields in depression interiors (Gliessman et al. 1981).

The investment in permanent agro-engineering implies that these systems were foci of intensive production, although the intensity undoubtedly varied, with increased frequency of cropping and heightened labor input per cropping period. Both terraced fields and raised plots require maintenance, tillage, weeding, and fertilization. Investigations of raised-field construction have revealed the presence of vegetal detritus from upland and wetland species (Miksicek 1980, 1982), which served as mulch, and the presence of night soil and manure (Pohl 1982; Turner and Harrison 1978, 350–52). Such applications increase supplies of organic matter, contributing to a rejuvenation of soil structure, and they supplement the supplies of available nutrients, thus compensating for the removal or loss of essential elements through harvest, leaching, or fixation into relatively insoluble compounds (Lal et al. 1975).

Another method of enhancing utilization of soil nutrients is through reliance on a large number of plant species and varieties with wide ranges of physical needs and tolerances for the limiting nutrient elements such as nitrogen, phosphorus, and sulphur. The evidence is less direct regarding the degree to which the Maya intensified the use of cropping time and space through the simultaneous or sequential growing of two or more different crops in the same field. Botanical materials recovered from structure and field contexts do indicate that the Maya utilized a multitude of plant forms, including both domesticated crops and wild species (Fish 1978, n.d.; Miksicek 1982; Miksicek et al. 1981; Turner and Miksicek 1981). Ethnohistoric descriptions of sixteenth-century Maya subsistence practices and analogies drawn from modern Maya agricultural techniques also suggest that a given production area may have supported a variety of usable species at any one time and that multicropping of various species was common (Barrera Marin, Barrera Vásquez, and López Franco 1976; Lundell 1933; Marcus 1982).

The integration of economically important botanical materials apparently took place on a number of different scales, which included open fields, perennial gardens, and orchards (Marcus 1982, 249). The mix of plant species implies an effective field or garden structure that to varying degrees avoids the diseases, pests, and soil problems associated with monocultures of genetically identical crops (Harris 1972; Netting 1977). In such systems, it is the vegetative structure—a complex pattern of foliage distributions, canopy heights, and nutrient demands—that reduces the impact of physical forces on the soil surfaces and maximizes the utilization and cycling of soil nutrients.

Although deforestation during the Maya periods is an undeniable fact and the diversity of native vegetation was undoubtedly reduced, the presence of many wild species in the paleobotanical record indicates that the Maya were well aware of that variety and its useful components. Some genetic stores were maintained, and the biological diversity of cropping systems was enhanced by the selective use of local species. Animal populations, like plant communities, become less plentiful and less diverse as forests are destroyed, and in the face of massive habitat destruction, the Maya may have practiced selective protection of some animal populations as well. Several terrestrial species may have constituted semidomesticated sources of protein that were maintained in the proximity of residential areas (Hamblin n.d.; Harris 1978; Rice and Rice 1979; Turner and Harrison 1978); pisciculture could have been practiced in some aquatic habitats in the vicinities of raised fields (Thompson 1974; Dahlin 1979).

In sum, it is apparent that the Maya initiated practices to reduce the regionwide processes of nutrient loss, deterioration of soil structure, destabilization of water flows, soil erosion, and loss of productive components of their environment. The results of the Maya "experiment" demonstrate that tropical forests are neither zones of unbounded fertility nor homogeneous zones in which cultivation redundancy is in order (Turner 1980). Theirs was a multihabitat and multitechnology system that was labor intensive, a system that relied on a primary motivation for increased production—a growing population—as the source of energy to run the system. Relatively speaking, it was an ecologically efficient regime that met increased demands for production through increased labor intensity and an increased agricultural land base.

The Maya adapted to the tropical forest environment over a long period, and a key to their success was undoubtedly the opportunity for sustained experimentation and evaluation. In the Yaxha-Sacnab basins, the environmental strains caused by soil depletion and alteration of the lacustrine ecosystem developed slowly, in tandem with low rates of population growth, too slowly to act as a mechanism to reduce overall population increase until at least Late Classic times. This statement is not meant to suggest that the Maya did not suffer constraints. Their growth, expansion, and intensification forced the Maya to consider more closely the processes of degradation. No data exist at present, however, indicating that the Maya agricultural system had reached its productive limits or that reduced productivity caused the civilization's "collapse." Certainly, some habitats or technologies were more vulnerable to strain than others, and the circumstantial juxtaposition of degradation and cultural decline in the Yaxha-Sacnab basins is theoretically enticing. But Maya responses to production problems were not only technological but social, religious, and political, and effective maintenance of an agro-economic infrastructure depended on cultural forces in addition to environmental ones. Both require further investigation.

The unresolved issue of the Maya "collapse" and the long-term success of the Maya civilization may foster spurious—and dangerous—complacency toward future economic development of the tropics if the relative rates of change are not kept in perspective. Current population trends in tropical areas engender a real sense of urgency about the work ahead. Tropical environments such as the Petén must be evaluated before modern populations obscure the details of ecosystem history so that pertinent information on successful, long-term adaptive strategies can be made available while it still might have some impact on future land use.

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