

ON THE MAYA COLLAPSE

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The collapse of Late Classic Maya civilization involved more than the disintegration of political structure. It involved a total system failure in which both centers and dependent villages were abandoned by elites and commoners alike. The lowland rainforest habitat where Maya civilization developed was not significantly reoccupied until comparatively recent times. The collapse was differential, in that centers in coastal areas or drier regions such as northern Yucatan were not depopulated to the same degree. The collapse of many Maya centers in the forested interior is here attributed to three interacting sets of variables: (1) nutritional stress, disease, and demographic instability; (2) agricultural intensification, monocropping, and degradation of the agrarian landscape; and (3) the relative absence of macroregional resource extraction structures. These factors had little impact on Maya populations living near the coast or in lowland areas not originally covered by tropical rainforests.

BETWEEN A.D. 300 AND 800 the ancient Maya developed a complex, hierarchically organized society in an environment we know today to be highly susceptible to environmental degradation and characterized by slow natural regeneration (R. E. W. Adams 1977; Culbert 1973; Gomez-Pompa and Vasquez-Yanez 1981; Rice and Rice 1984; Wilkerson 1985). In the Late Classic period (A.D. 600–800) substantial parts of the Maya Lowlands were densely occupied by populations of peasant farmers. Because most cultivable sections of the Peten and adjacent regions already had been brought under intensive cultivation, these farming populations made great demands on their tropical rainforest habitat. Classic populations combined dense settlement and intense agricultural production in physiographic regions as diverse as the Pasion and Usumacinta river drainages, the *bajos* and lakes of the central Peten, slopelands in the Rio Bec region, the river valleys and wetlands of Belize, and the drier regions in the northern section of the Yucatan Peninsula (Figure 1). It now seems likely that the very success of the Classic Maya at settling and developing the Lowland forest laid the foundation for the collapse of southern Lowland Maya civilization at the end of the Late Classic period.

The growth and rapid decline of Maya civilization in the southern Lowlands provide a sharp contrast with other areas where ancient civilizations developed. In semiarid regions such as Central Mexico, the Andes, and greater Mesopotamia, periods of relatively sustained growth and development, separated by phases of political fragmentation, appear to be the norm throughout the prehistoric sequence. The sociopolitical systems of these areas all faced the problem of provisioning increasingly larger populations on circumscribed agricultural landscapes. The trajectory of cultural development in the Maya Lowlands, however, was different. The florescence of Classic period Maya civilization in the Peten and adjacent areas was followed not by periods of balkanization

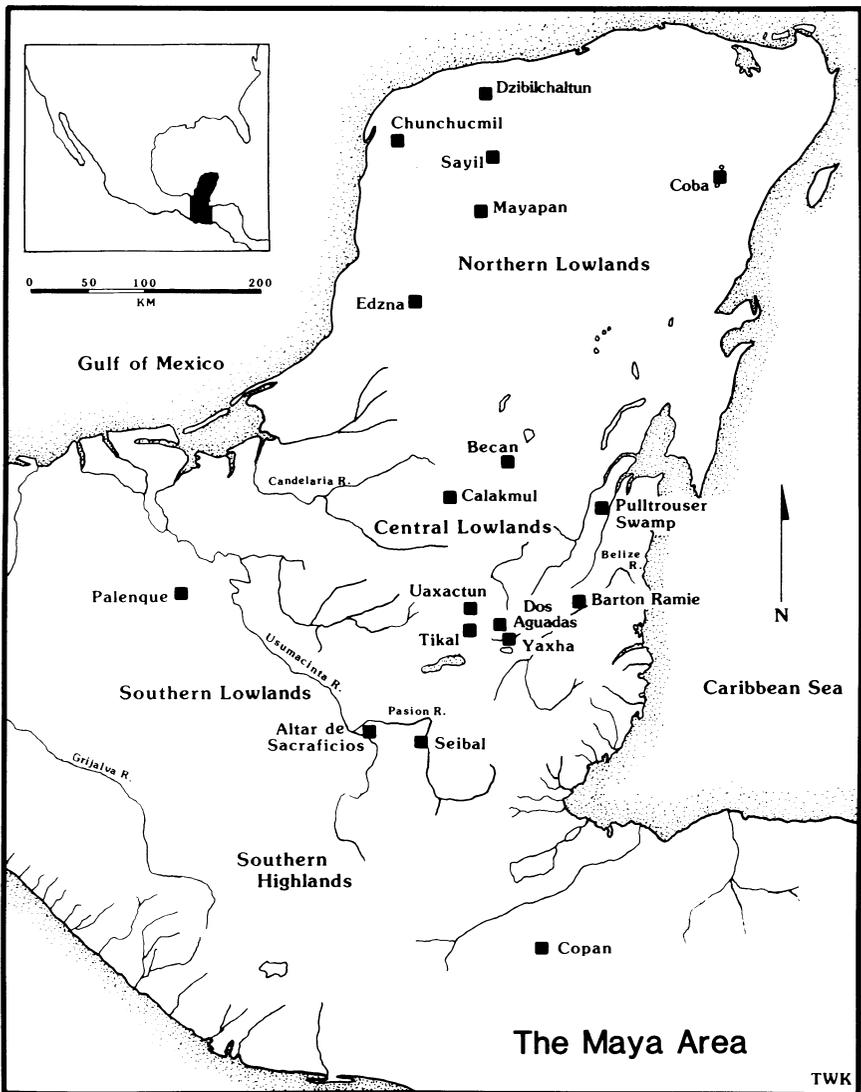


Figure 1. Map of the Maya Region

and regrowth but by wholesale system collapse, with major parts of the Lowlands abandoned until comparatively recent times. In the Maya case we will argue that the need to sustain progressively larger populations placed severe constraints on the food production base which precluded further development, rendered the system inviable, and prevented recovery. In this paper we will focus on the problem of maintaining intensive sustained-yield agroecosystems in a rainforest environment. Agricultural utilization and degradation of the tropical forest habitat by growing populations of peasant farmers have evidently been a common feature of land use from prehistoric times to the present. The

fall of Classic Maya civilization in the ninth century, then, is seen here as the negative outcome of a series of interrelated biological, demographic, and socioenvironmental problems faced by all archaic civilizations and is an important object lesson for the contemporary use and development of the tropics.

Arguments concerning causes of the Maya collapse have included such factors as inherent environmental limitations of the rainforest habitat, climatic perturbations, soil exhaustion, famine, disease, civil strife, and foreign invasion (Culbert 1973). As Lowe (1985) has recently pointed out, these arguments are generally inadequate because they lack systemic character. Other more integrative multifactor models of the collapse have been criticized for their inability to explain known patterns of variability in the Maya Lowlands. One of the most intriguing aspects of the Maya "experiment" in civilization was the initial growth and success of Classic populations at utilizing the Lowland tropical rainforest and transforming it into a highly productive agroecosystem. Evidence for landscape modification and sustained agricultural intensification continues to accumulate for the Maya Lowlands from the Preclassic until Late Classic times. Why then did this seemingly successful and long-enduring experiment in civilization finally fail at the end of the Late Classic?

It is our position that, although initially successful, Maya populations eventually approached the limits of the southern Lowland resource base at a time when the cumulative effects of malnutrition and disease made the maintenance of an elaborate agrotechnology increasingly difficult. The combined effects of environmental degradation due to the slow regenerative capacity of Lowland forests and soils, physiological stresses related to inadequate nutrition and disease infestations, and the relative absence of regional resource extraction networks led to demographic instability, the collapse of the agricultural system, and the eventual abandonment of a majority of the southern Lowland centers by elites and nonelites alike.¹ Another property of the Maya collapse is that it was spatially restricted. In contrast to more landlocked portions of the southern Lowlands, populations located in coastal areas where marine resources provided an important component to subsistence (e.g., Belize), in areas where soils were less susceptible to degradation and/or had a higher regenerative capacity (e.g., highland Guatemala), or in areas where alternative resources such as salt were available (e.g., northern Yucatan) were not disrupted to the same degree. Because the structure of the resource base utilized by populations inhabiting these areas was different, a collapse phenomenon would not be expected, although rearrangements in local system organization might be. This is precisely what the archaeological record indicates.

STRUCTURE OF THE LOWLAND MAYA RESOURCE BASE

Our treatment of the structure of the Lowland Maya resource base is divided into three parts. First, we present data on Maya settlement patterns which indicate that population densities reached peak levels throughout the Lowlands in the Late Classic. Next, we discuss both archaeologically known and potential

modes of agricultural production, focusing on agrotechnologies applied to slope-land, riverine, lake margin, and bajo environments. Third, we look at the location and availability of other resources, particularly hunted game, which may have provided critical dietary supplements. Inherent difficulties faced by growing farming populations utilizing the tropical forest are discussed. These difficulties are related to the inability of the agroecosystem to sustain high production levels over time without degradation.

Settlement and Population Density

Table 1 provides settlement densities and population estimates based on house-mound counts for a broad sample of Lowland sites. The evidence of high population densities surrounding Classic Maya centers shows that extensive, shifting cultivation probably could not have supported more than a fraction of the Maya population. Studies of contemporary swidden cultivators document that shifting cultivation in the Maya area normally supports less than eighty persons per square kilometer (Cowgill 1962; Nations and Nigh 1980). This figure falls well below Classic period population estimates for the Lowlands based on survey data from Maya centers and their rural sustaining areas. While some scholars (e.g., Sanders 1973) have suggested that all house mounds might not have been occupied simultaneously, little actual evidence exists for noncontemporaneity or for seasonal occupation of structures from the heart of the southern Maya Lowlands. In fact, the structural redundancy in the pattern of Maya residential settlement from center to more rural periphery suggests year-round occupation for most Classic residences. Ceramic evidence from a number of Lowland centers such as Becan (Thomas 1981), Tikal (Fry 1969; Culbert and Kosakowsky 1985; Puleston 1973), Seibal (Tourtellot 1982), and Yaxha (D. Rice 1978; Rice and Rice 1985) indicates that populations reached a peak in the Late Classic when most, if not all, structures were occupied. High population densities were not restricted to the largest Maya centers and their immediate peripheries. House-mound counts from survey transects between major Maya centers in the Peten show that population densities in rural areas were also high (Culbert n.d.). Settlement-pattern data from around Uaymil also suggest continuously high mound frequencies across most of southern Quintana Roo (Harrison 1981, 1982). To the south in northern Belize, mound counts are again quite high (ca. 107 mounds per square kilometer), even in the relatively rural Late Classic communities surrounding Pulltrouser Swamp (Harrison 1983).

Maya farmers evidently occupied a densely populated landscape in a way more akin to the dense settlement systems of central Africa than to the pattern of nucleated settlement found in Central Mexico (Sanders 1976, 1981; Netting 1977). Population increase eventually led to a "filling up" of the habitable landscape, a process common to many archaic civilizations dependent on simple agricultural production. According to Culbert (n.d.), the demographic trajectory at large Maya sites such as Tikal was exponential, with populations experiencing curvilinear growth throughout the Classic period. Continuous and fairly even

TABLE 1
Residential Structures and Population Density at
Late Classic Lowland Maya Sites

Settlement Location	Structure Clusters or House Mounds (per sq. km.)	Estimated Population Density (per sq. km.)	Reference
Uaxactun Site center	112	450	Puleston 1974 Ricketson and Ricketson 1937 Puleston 1973
Dos Aguadas	—	222	Bullard 1960
Tikal			
Center	235	713	Puleston 1974
Periphery	145	—	Carr and Hazard 1961
Survey strip	119	600–700	Puleston 1973 Haviland 1966
Major Peten sites			
Center	—	600–1000	Puleston 1973
Periphery	—	200–300	
Seibal			
Center	101	450–590	Tourtellot 1982
Periphery	53		Tourtellot 1982
Becan–Rio Bec region	134	503–670	Turner 1983b Turner 1974
Becan			
Site area	222	900	Thomas 1981
Barton Ramie (Belize River)	131	735	Willey et al. 1965 R.E.W. Adams 1981
Dzibilchaltun	397	2000	Kurjack and Garza T. 1981
Coba			
Central zone	309	1400	Folan, Kintz, and Fletcher 1983
Chunchucmil	400	—	Vlcek, Garza de Gonzales, and Kurjack 1978
Copan	192	—	Willey and Leventhal 1979

habitation of the landscape meant that Maya farmers probably brought a majority of Lowland habitats into agricultural production at the same time. That much of the forest had been removed is supported by palynological evidence from the Peten (Rice 1978) and northern Belize (Wiseman 1978).

Certain components of the tropical forest environment were transformed into highly productive and resilient agricultural systems, the raised field systems in a number of wetland environmental settings being one example. Slope-lands were also intensively cultivated; however, with the exception of kitchen gardening near residences, high yields cannot be maintained on intensively cultivated slopeland plots, and their repeated cultivation may actually enhance degradation processes, thus severely limiting their productive potential. The expansion of dense settlement was associated with an increased number of buildings per unit of land, and this increase in the area covered by structures, combined with agricultural intensification on shallow tropical forest soils, altered local hydrology and accelerated rates of erosion (Rice and Rice 1984). The extension of systems of intensive slopeland agriculture over a large proportion of the landscape, then, would have increased the susceptibility of segments of the food production system to degradation processes and decreased its capacity for resilience. Slopeland agricultural intensification and its adverse impact on crop yields and exacerbation of erosional processes, however, cannot by themselves explain the timing and all-encompassing nature of the Maya collapse.

Known and Potential Agrotechnologies

Recent population estimates for the Lowlands attest to the presence of a dense population spread over much of the available agrarian land (Ashmore 1981). Concomitant with the growth in our knowledge about Lowland Maya settlement patterns and the rejection of the swidden hypothesis has been the accumulation of hard evidence that the ancient Maya utilized a complex and diverse range of agrotechnologies (Harrison and Turner 1978). Throughout the varied habitats of the Lowlands, it appears that Maya farmers combined field modification (where existing soil, moisture, and slope characteristics of agricultural plots are altered) with spatially diversified cropping techniques (where different crop mixes and fallow cycles are practiced within the same general settlement zone) in order to increase subsistence yields and feed an increasingly dense population.

Evidence of intensive agrotechnologies in the Lowlands has been documented at a number of sites. These are listed in Table 2. In light of the obvious inadequacy of swidden cultivation to support estimated population densities, potentially applicable agrotechnologies are also suggested in Table 2. These alternative methods of subsistence production may have provided the Maya with increased yields at varying costs in labor investment and environmental stability.

Shifting agriculture is conducted on *dryland outfield plots* which are located at some distance from the more densely settled residential areas. These fields are not irrigated, receive little or no fertilizer, and are structurally and func-

TABLE 2
Known and Potential Agrotechnologies for
Different Late Classic Lowland Maya Sites

Site	Known Agricultural Features	Potential Agrotechnologies	References
Tikal	terraces (near Flores)	shifting agriculture in uplands; infield gardens; orchards; some terraces	Puleston 1973 Turner 1974
Uaxactun	terraces (near Flores)	shifting agriculture in uplands; infield gardens; orchards; some terraces	Puleston 1973 Turner 1974
Rio Bec (Becan)	terraces; raised fields	shifting agriculture in uplands; terraces; raised fields; infield gardens (farmsteads); orchards	Turner 1983b R.E.W. Adams 1981
Northern Belize (Pulltrouser Swamp)	raised fields	shifting agriculture in uplands; raised fields; infield gardens; orchards	Turner and Harrison 1983
Pasion region (Seibal)	raised or channelized fields	intensive flood water farming on alluvium; raised or channelized fields; shifting agriculture in uplands; infield gardens; orchards	R.E.W. Adams 1983 Tourtellot 1982
Belize River (Barton Ramie)	terraces	shifting agriculture on uplands; intensive flood water farming on alluvium; infield gardens; orchards	Willey et al. 1965
Quintana Roo	raised fields	shifting agriculture on uplands; raised fields; infield gardens; orchards	Harrison 1981, 1982
Campeche N.W. Yucatan (Edzna)	irrigation canals (reservoirs)	shifting agriculture on uplands; infield gardens; irrigated fields; orchards	Matheny 1978
Coba	kitchen gardens	shifting agriculture on uplands; raised fields on lakes; infield gardens; orchards; pisciculture	Folan, Kintz and Fletcher 1983

tionally equivalent to the contemporary Mesoamerican outfield *milpa*. Maya farmers could have decreased fallow periods on outfield milpa plots and turned extensive swidden zones into areas of annual cropping. The problems of maintaining soil fertility on these plots, though, greatly limit the long-term productive capacity of this agricultural strategy.

Production levels on dryland outfield plots cropped in maize decrease markedly through time because soil nutrients critical for plant growth decline as parcels are consecutively cultivated. Measurements on experimental plots in the Peten, for example, demonstrate that the amounts of nitrogen, potassium, phosphorus, and magnesium increase with each fallow year, indicating that the amounts available for plant utilization decrease steadily with each year of successive cultivation (Urrutia 1967). The amount of nitrogen available is particularly important because it controls seed productivity and the proportion of protein present and governs the utilization of potassium and phosphorus, which are essential for starch formation, seed maturation, and chlorophyll development in leaf tissues (Donahue, Shickluna, and Robertson 1971). Soil fertility drops rapidly in the tropics because most nutrients critical for plant growth are either locked up in the forest canopy or present only in the thin layer of leaf litter decaying on the surface. With removal of the forest, leafy matter no longer accumulates on the surface, and a rapid drop in the nutrients required for plant productivity occurs. Prolonged deflection of the forest to crop plants, successional species, or exposed earth also leads to a breakdown in soil structure, soil compaction, loss of surface permeability, and reduced infiltration, all of which accelerate erosion.

Crop losses also occur because weeds, insect infestations, and plant diseases become more significant problems the longer a field is under successive cultivation. These problems are particularly severe when fields are monocropped or planted in only a few species. Most plant predators in the humid tropics are specialists. Although biological diversity is high and the density of each plant species is low in climax settings (Colinvaux 1973; Margalef 1968), forest clearance greatly reduces the number of different species present and concentrates plant-specific predators in the area around agricultural plots. Although this process generally takes several years to be felt, as predators react to changes in the density and distribution of plant prey, it ultimately contributes to reductions in yields.

Workloads also increase as slopelands in the humid tropics are used more frequently (Boserup 1965; Sanders 1976; Steggerda 1941). This increase in labor is primarily a function of the need for more frequent cultivation as competition from weeds and grasses becomes more pronounced after several consecutive years of land use. Since weedy species are not numerous on the forest floor in climax situations, competition generally does not pose a serious problem during the first year after forest removal. Their numbers, however, increase markedly thereafter because the extra amount of solar radiation reaching the surface creates optimal conditions for plant succession (Daubenmire 1968). Weeds also exhibit growth profiles comparable to cereals and hence

effectively compete for both critical nutrients and space. Extra labor must therefore be allocated for their clearance in order to maintain production levels. The total time devoted to weeding is often considerable, not uncommonly amounting to 50 percent of all labor expended. More labor may also be devoted to fencing and field preparation before planting. So, as the frequency of cropping increases, the overall efficiency of the system declines. Farmers can hedge against drops in productivity by cultivating more space; but because labor expenditures per unit area have risen, with intensification greater and greater constraints are placed on the total amount of land farmers can bring under simultaneous cultivation.

Complex cropping techniques, where cultigens with varying mineral and nutrient requirements are cultivated together, could have been used to help maintain soil fertility and lengthen field productivity (Norman 1979; Sanchez 1973, 1976; Wilken 1971). Mixed species gardening is less susceptible to land degradation by erosion and compaction because crop mixes tend to create a tiered vegetative cover which shields the ground surface from the deleterious effects of rain water and baking by the sun. Monocropped fields, unlike mixed fields, are normally cropped at one time leaving a block of land denuded and subject to compaction or mass wastage. Complex techniques in outfield contexts are normally practiced at lower population densities (Nations and Nigh 1980). However, mixed planting on outfield plots with shortened fallow periods eventually faces the same process of declining yields due to decreased fertility and soil exhaustion as do monocropped plots on permanently and semipermanently cultivated fields. Mixed cropping, therefore, could not have solved the Maya farmer's long-term problem of declining yields and decreased productivity in areas where forest succession had been permanently deflected to short fallow.

Mulching and the deposition of night soil are two means of artificial enrichment by which the Maya may have tried to maintain soil structure and replenish nutrients lost through frequent cropping on outfields (Rice and Rice 1984). Mulching, we suspect, would not have solved the problem of nutrient loss, since the prevailing mode of transport was human powered and slopeland sources of mulch were probably few in number by the Late Classic. Literally tons of organic matter would have been required for each hectare under cultivation, and the major source of this material would have been bajos. Since mulching would have required transport uphill by human carriers, any increases in production may well have been offset by the extra labor expenditures involved. The application of large amounts of night soil, while energetically feasible at infield garden locations, is also impractical at more distant outfield locations where human-powered transport costs are high.

Because of all these problems, decreases in productivity would have rapidly favored abandonment of outfields subject to decreased fallow unless they were located on annually flooded alluvial bottomlands or on terraced upland slopes where soil nutrients are partially replenished by the retention of slope-washed sediments. However, annual cropping on alluvial bottomlands and along natural

river terraces is areally restricted in the Maya Lowlands due to the limited amount of land available in narrow river valleys and to bajo flooding in wider river courses. The terracing of upland slopes, then, would have been one of the prime means by which the Maya could have tried to increase outfield agricultural production.

Terracing slopelands is one way to check erosional processes. Terraces also promote soil buildup and limit nutrient loss by trapping inorganic particles and leafy matter that would normally be washed downslope. Terracing may serve a variety of other functions, including moisture retention, protection from high winds, and retardation of phosphate loss by colluvial processes. Diverse cropping regimes, with field borders planted in economically useful trees, is another way to inhibit soil loss, because the species planted form a multitiered community of vegetation and have different root system structures. Moreover, since the species planted have varying physical requirements, the utilization of soil nutrients is maximized. The evidence for terracing from the Maya Lowlands is substantial and suggests the extensive utilization of this technique in the Rio Bec settlement area, in the central Peten, and along the Belize River (Donkin 1979; Puleston 1973; Turner 1979, 1983a; Willey et. al. 1965). Shortened fallow outside of these specialized settings would have been subject to decreased yields per unit of labor input over time and to accelerated rates of erosion where agricultural plots were more frequently denuded between plantings. The same problems would have also occurred in areas like the Peten if polycultural cropping was replaced by monocropping in maize during the Late Classic.

Erosion is most severe in situations where the slope angle is great, large contiguous areas of ground surface are directly exposed to physical forces, and rainfall patterns involve the deposition of large amounts of precipitation, often in torrential downpours. In the Basin of Mexico, for instance, archaeological data suggest that a major erosional episode occurred in the Guadalupe Range during the Middle Formative (Sanders and Santley 1977). This evidence of degradation is associated with shift in settlements from sloping localities in the piedmont to the alluvial plain and with the adoption of floodwater and canal irrigation (Nichols 1982; Santley 1977). The same sequence of events may have occurred in the Teotihuacan Valley several centuries later. We suspect that the Guadalupe Range eroded at such an early date because large areas of sloping terrain had been denuded of vegetation for dry farming, which accelerated rates of soil loss and forced villages to exploit alluvial bottomlands. Such erosion of short-fallowed slopeland agricultural plots would have also had important consequences for the manipulation of intensively cultivated wetland settings in the Maya Lowlands where interior drainage is common.

Archaeological evidence suggests that flooded bajos, lake margins, and low-lying riverine settings were prime locations utilized by Maya farmers for the construction of raised and channelized fields. These are highly resilient and productive agrotechnologies that would have maintained high yields on a continuous or semicontinuous basis (R.E.W. Adams, Brown, and Culbert 1981;

Harrison 1977, 1978; Siemans 1978, 1982; Turner 1974; Turner and Harrison 1983). *Raised fields* involve the excavation of a grid of canals to facilitate drainage and lower the watertable, with the soil piled next to the canals to elevate the field level and create a relatively dry planting surface. *Channelized fields*, on the other hand, consist of long trenches excavated into wetland margins to enhance deeper water drainage and bring water to the dryer interior soils. Incidentally, evidence for the actual canal irrigation of dryland agricultural plots from Edzna in Campeche is problematical and suggests that this form of hydraulic manipulation was rare in the Maya Lowlands (Matheny 1978). If managed properly, raised fields can produce substantial yields each year without degradation, and it is possible to schedule more than one crop per year. This situation is very much unlike that on slopelands, where production levels drop each year under successive use. The major drawback of these systems is the large amount of labor required for yearly maintenance: on the order of 200–250 man-days per hectare of cultivated space (Sanders, Parsons, and Santley 1979; Turner 1983a).

Earlier estimates of the area affected by channelization and field raising in the Maya Lowlands ran into the hundreds of thousands of hectares for northern Belize, Quintana Roo, and the Peten. Subsequent ground verification and historical research has tempered these estimates but not substantially reduced the probable spatial extent of these features (R.E.W. Adams, Brown, and Culbert 1981; Millet Camara 1984). Muck and soil rich in decaying organic matter can be excavated from canal bottoms and applied to field surfaces to maintain fertility. High levels of agricultural production can be maintained indefinitely in these contexts, as is evidenced by the continuing productivity of the Lake Chalco-Xochimilco *chinampa* system in the Basin of Mexico after more than five centuries of use (Armillas 1971; Parsons 1976). Intensive annual cropping on upland soils surrounding areas of wetland cultivation would have had long-term negative effects on raised and channelized agricultural systems. Slopeland erosion increases rates of downstream sedimentation, slowly decreasing the area of land available for raised field cultivation. Sedimentation also reduces the amount of organic muck available for use as mulch to maintain soil fertility, which would have decreased yields on this critical and highly productive component of the Lowland agroecosystem.

Another agrotechnology available to the Classic Maya was *infield gardening*, a system of cultivation where arable land adjacent to residences within settlements is brought under intensive cultivation. Infield or kitchen gardening, a common feature of subsistence in the humid tropics, is an important source of food, medicine, condiments, building material, and fuel (E. Anderson 1952; Kimber 1966, 1973; Killion 1985; Wilken 1971). The ethnohistoric and ethnographic record indicates that horticultural practices within settlements were widespread among the Lowland Maya (Landa 1938; Lundell 1938; Redfield and Villa-Rojas 1934; Roys 1943; Scholes and Roys 1968; Steggerda 1941; Wilken 1971). Puleston (1973), Folan, Kintz, and Fletcher (1983), and Sanders (1981) have provided convincing arguments for the importance of dooryard and infield

gardening at Classic Maya settlements. Archaeological evidence for kitchen gardening is also known for other parts of Mesoamerica during the Formative period (Santley et al. 1984; Sheets 1983).

The deposition of night soil and other household refuse acts to increase the fertility of arable land within settlements. According to Ann Kirkby (1973:120), a family of five individuals can produce enough manure each year to fertilize an area of about four hundred square meters. If enrichment was necessary every two to three years, approximately one-tenth of one hectare could have been fertilized with night soil in the immediate vicinity of the residence. The infield areas between residences within Maya settlements therefore represent naturally more fertile and agriculturally more resilient settings for cultivation than do dryland outfield plots. Tourtellot (1982) suggests that approximately one hectare of cultivable land was available to each residential unit at Seibal in Late Classic times. Table 3 presents the mean amount of arable land available to residential units visible at the surface within the residential cores of a sample of Late Classic Lowland centers. Crop production on this unoccupied land can be expected to have given higher and more sustainable yields than did dryland settings where fertilization was energetically less feasible. While infield plots could never have provided all of the staple dietary needs of Lowland settlements, they would have produced important food and nutritional supplements without suffering the decreases in productivity to which outfield plots were subject.

To recapitulate, Classic Maya farming populations would have faced the problem of insufficient yields if they relied solely on dryland shifting cultivation at relatively high population densities. Where feasible, terracing and raised or channelized field construction would have increased the overall productivity of the agricultural system. Infield gardening and orchard production were applicable to virtually all Lowland settings. More intensive forms of shifting cultivation with variable rates of fallow could have been practiced on the remaining segments of the landscape at increasingly lower levels of productivity over time.

TABLE 3
Estimates of Cultivable Land per Residential Unit
at Late Classic Lowland Maya Sites

Site	Hectares per Residential Unit	Reference
Central Tikal	.16-.2	Puleston 1983
Peripheral Tikal	.5-1.5	Puleston 1983
Seibal	.98	Tourtellot 1982
Dos Aguadas	.6	Bullard 1960
Chunchucmil	.25	Vlcek, Garza de Gonzales, and Kurjack 1978
Sayil	.69	Sabloff et. al. 1985
Coba	.81	Folan, Kintz, and Fletcher 1983
Mayapan (Late Classic)	.25	Smith 1962

Secondary Resource Utilization

Hunted game, gathered plants, and aquatic resources are important components in many food production systems because they provide critical nutrients lacking in agricultural crops. Of all the secondary resources utilized in prehispanic Mesoamerica, only three are discussed here: deer, fish, and the proteinaceous algae, *Spirulina geitleri*. In many landlocked parts of Mexico the white-tailed deer was by far the most important species of terrestrial fauna hunted. Fishing, of course, would have been restricted to riverine, lacustrine, and marine settings, while *Spirulina* procurement would have been confined to relatively saline lake situations.

White-tailed deer are browsers and thrive best in woodland and deciduous forest biomes (Flannery 1968; Leopold 1959). The deer biomass potentially available is primarily a function of the amount of browsing habitat present and the distribution of that habitat relative to human predators. In many densely populated areas, agricultural land use modifies local plant synecology, producing a habitat optimal for white-tailed deer. The degree to which agricultural intensification and modification of the tropical rainforest environment affected Lowland deer populations can be demonstrated by comparing the spatial distribution of cropland and potential game preserves in the Maya Lowlands with that in central highland Mexico. In Central Mexico the primary zone under agricultural exploitation, the alluvial plain and the lower slopes of the adjacent piedmont, was not a habitat in which white-tailed deer thrive naturally in the wild (Sanders, Parsons, and Santley 1979). Agricultural intensification thus would have had little negative impact on the density of woodland/forest browsers once canal irrigation became the dominant mode of agricultural subsistence in Classic times. In fact, intensification may have actually increased the number of deer available locally by creating browsing habitats on fallow agricultural land on the alluvial plain, while maintaining reserves in upland forests.

In the Maya Lowlands, on the other hand, slopeland agriculture gradually resulted in the removal of the forest and the destruction of the habitat of many species of terrestrial fauna. Although intensification may have increased the density of certain animal species as more and more of the forest was converted into various stages of regrowth, eventually white-tailed deer must have become less plentiful as hunting levels exceeded rates of replacement. It is likely, therefore, that by Late Classic times many species of terrestrial fauna had been almost totally decimated throughout large portions of the southern Lowlands. Hence, while spatial segregation of agricultural zones and terrestrial faunal preserves may have acted to maintain at least some game stocks in Central Mexico, congruity in the distribution of agriculture and game territories in degraded Lowland forest habitats eventually led to the virtual extinction of critical game reserves. Although rodents and other small mammals may have provided some meat, the Late Classic Maya, we believe, would have been hard pressed to find the necessary supplements of animal protein in their agriculturally dominated landscapes.

Fish and aquatic mammals are another source of protein. The estuarine and

marine habitats of the Gulf of Mexico and Caribbean Sea support some of the richest saltwater fisheries in the New World. Fish are especially rich in protein, and the kind of protein present is of high biological value (Church and Church 1975). Although marine fauna are consumed today throughout Mexico, their widespread utilization is primarily due to recent improvements in transportation and refrigeration technology. Archaeological evidence indicates that aquatic fauna were a major component only in the diet of coastal populations (Hamblin 1984; Healy 1983; Wing 1978). Although not many archaeofaunas have been described for sites from inland Mesoamerica, those few that have been reported contain very few marine resources (Drennan 1976; Pohl 1983; Starbuck 1975; Whalen 1981). While marine fish could have been filleted, dried, and then shipped inland, there is no evidence that the Maya developed such a production-distribution system. Some fish were probably obtained from perennially flooded wetlands, rivers, and inland lakes, but given the high population densities Mayanists have suggested for the Late Classic, the total amount of freshwater fauna consumed per capita was undoubtedly quite small.

Besides fish, lakes and marshes may also provide other resources rich in critical nutrients. The proteinaceous algae, *Spirulina geitleri*, was used by the Aztecs as an important additive to many sauces (Furst 1978). By weight *Spirulina* contains 65–70 percent raw protein, of which 84 percent is digestible; and tryptophan, the essential amino acid lacking in maize-based diets, is present in quantities three times that of deer and twenty times that of corn (FAO 1970; Pirie 1975a; Santley and Rose 1979). Also, *Spirulina* has a very favorable leucine/isoleucine ratio and is rich in salt and in many vitamins. Consumption of only minor amounts of this resource therefore would have allayed many of the nutritional problems associated with a maize-based diet. However, *Spirulina* only grows in highly alkaline lakes (pH 9–10) and consequently would not have been present in the Maya Lowlands. *Chlorella* and other species of blue-green algae rich in protein, essential amino acids, and other nutrients do thrive in the freshwater lakes and marshes which abound in the Maya Lowlands. Experimental research, however, indicates that they produce severe diarrhea (Pirie 1975b). The physiological utility of such species is thus quite limited, so it is doubtful that they were ever utilized as a dietary supplement by the ancient Maya.

Through time, the juxtaposition of declining yields on intensively cultivated agricultural landscapes and the increasing lack of terrestrial game, fish, and aquatic resources posed insurmountable problems to Maya farmers unable to open up new segments of the landscape for agricultural production. The high Lowland population densities suggest that virtually all segments of the Lowlands suitable for settlement had been filled by Late Classic times. Hence, expansion of the system was impossible because most of the surrounding landscape was already occupied by similar groups facing the same problems. Late Classic Maya populations were consequently faced with the difficult problem of solving their food production needs with the resource base at hand.

THE CLASSIC MAYA COLLAPSE

In our opinion three variables played major causal roles in precipitating the Maya collapse: (1) demographic instability, (2) agricultural failure, and (3) the absence of macroregional resource extraction structures. The general picture of Late Classic Maya subsistence outlined above involves a multiple-technology agricultural system greatly reliant on terrace or short-fallow agriculture and raised fields but probably augmented by kitchen gardening, orchard cultivation, and perhaps pisciculture in freshwater aquatic habitats. Large portions of the cultivable landscape were probably exploited at high levels of intensification, and agricultural production was undoubtedly geared to a few staples, with other plant resources, meat, and fish consumed only in small amounts as dietary supplements.

Nutritional Stress, Disease, and Demographic Instability

According to Don Rice (1978:55), "By the end of the Late Classic period the production of all foodstuffs, including, to some degree, ramon, was probably strained." The staples which were probably grown were rich in calories but notoriously poor in other nutrients. A maize-based diet, supplemented with beans, squash, and other plants, does not contain all of the nutrients and amino acids necessary for a well-balanced diet (Santley and Rose 1979). While beans make up for the inadequate amount of the essential amino acid lysine present in corn, both resources are deficient in tryptophan. The metabolism of tryptophan is closely linked to the endogenous production of niacin (Aguirre et al. 1953). If the tryptophan in maize is not supplemented from other sources, severe niacin deficiencies will develop. In addition, the levels of methionine and phenylalanine present in maize are barely adequate, and the leucine/isoleucine ratio is distinctly unfavorable, which interferes with the metabolism of what tryptophan is present. The protein in maize is stored primarily in two classes: zein, which is readily available in a dilute saline solution, and glutelin, which is largely unextractable by the body unless the maize is processed with alkali (Katz, Hediger, and Valleroy 1975). The zein portion is extremely deficient in lysine and tryptophan, while the glutelin fraction is rich in high-quality protein. Processing maize in lime liberates the glutelin fraction, as well as improving the leucine/isoleucine ratio. Although maize has moderate amounts of iron, it also contains phytic acid (phytate) which inhibits iron absorption (Ashworth et al. 1973; El Najjar et al. 1976). Successful hemoglobin synthesis will therefore be significantly impaired unless iron is supplied from other sources. Because of the limiting effects of phytic acid, maize-based diets are also deficient in zinc (Lloyd, McDonald, and Crampton 1978).

Root crops and ramon have also been suggested as staples for the Maya (Bronson 1966; Puleston 1968), but whether these foodstuffs were ever utilized in significant amounts is undetermined. However, even if ramon and root crops comprised the mainstay of Maya subsistence, they would not have allayed the

nutritional deficiencies just discussed. Root crops, while rich in carbohydrates, provide only very limited amounts of other nutrients, especially protein (Wu Leung 1961). Ramon, contrary to Puleston's assertions, is not significantly richer than maize in most nutrients except calcium. Ramon seeds contain 11.4–13.4 percent protein by weight compared to 8–10 percent for maize on the average (Puleston 1968; Wu Leung 1961). Increased reliance on beans is another possibility, but beans are not particularly high in tryptophan and methionine (Church and Church 1975). These essential amino acids are amply represented in fish and meat. But fish, it would appear, were consumed mainly by Maya living in coastal habitats, one part of the Maya landscape which never experienced a demographic crash as severe as that which hit landlocked sections of the southern Lowlands. And deer are not particularly abundant in forests in the humid tropics (Leopold 1959). While forest clearance may have increased deer densities and deer can withstand high levels of predation, it is unlikely, given the high population densities Mayanists have suggested for the southern Lowlands (Culbert n.d.), that they accounted for more than a fraction of one percent of all the foodstuffs consumed in the Late Classic. In the Basin of Mexico, for example, the dietary contribution of white-tailed deer would have amounted to only 1.65 grams/person/day (or about 0.3 percent of the diet), assuming a human population of 250,000, optimal deer densities, no overkills, no imported game, complementary predation by wolves and large cats, and increases in deer numbers on fallow agricultural land (Sanders, Parsons, and Santley 1979; Santley and Rose 1979). Levels of intake in the Maya Lowlands were probably even less since human population densities were probably greater there than in the Basin of Mexico.

The diet of the Late Classic Maya thus involved a heavy focus on domesticated grains. Maize was the principal food, supplemented by small amounts of beans, squash, ramon, tropical fruits, and perhaps root crops. Although adequate amounts of raw protein were probably ingested, the biological value of that protein was undoubtedly quite low. It seems likely that levels of tryptophan and methionine consumption were grossly inadequate. These deficiencies, together with the unfavorable leucine/isoleucine ratio and the intake of large quantities of phytate, produced niacin, zinc, and iron deficiencies.

Nutritional problems of this sort have great impact on the structure of human populations. The relationship between nutrition and human reproductive performance is dual-directional. On the one hand, a female's nutritional status has an effect on her chances of conceiving, upon the outcome of pregnancy, on the probability of infant survival, on birth interval, on age of menarche and menopause, and on her life expectancy. Rates of fetal wastage and infant mortality and the probability of a female dying upon reaching child-bearing age are much higher in populations which are malnourished (Delgado et al. 1978; Bongaarts and Delgado 1979; Thomson and Hytten 1973). Malnourished women also exhibit later age at menarche, earlier age at menopause, and longer birth intervals than do females who are better nourished (Carael 1978; Frisch 1975, 1976; Stein and Susser 1975). On the other hand, births that are spaced too

closely have a negative effect on the mother's nutritional status. This syndrome, known as "maternal depletion," is cumulative with each reproductive cycle (Jelliffe 1973). Dietary deficiencies in iron and zinc may play a major role in impairing successful reproductive performance and enhancing rates of miscarriages, stillbirths, and infant mortality (Brasel 1978; Lloyd, McDonald, and Crampton 1978). Zinc also plays an important role in cell-mediated immunity, and both parasitic infection and malnutrition, common problems in the humid tropics, lead to increased zinc depletion, which affects the body's immunological response (Mata 1984; Solomons and Shripton 1984).

Dietary proteins are perhaps the most important nutrients ingested because they supply the amino acids and nitrogen necessary for the synthesis of body proteins and other nitrogen-containing compounds (Lloyd, McDonald, and Crampton 1978). Amino acids are essential for growth, development, gestation, lactation, and the production of enzymes, antibodies, and serum proteins. Of the twenty-two amino acids of biological importance, eight are essential; i.e., they must be ingested in adequate amounts and in proper proportion or protein deficiency results. As indicated above, a major problem with which the Maya had to deal was the limited amount of the essential amino acid tryptophan they ingested, combined with the low level of their methionine intake and the unfavorable leucine/isoleucine ratio prevalent in their maize-rich diets. Protein deprivation also aggravates rates of infant mortality and often results in lower weight babies and sometimes in infants with "nutritional brain damage" (Bongaarts and Delgado 1979; Jelliffe 1973). In addition, "age at weaning may be earlier in populations subsisting largely on grains and utilizing boiling techniques for preparing foods than in populations whose diet contains less carbohydrates and a larger proportion of meat" (Santley and Rose 1979:190). Thus, early weaning, while returning the mother to the reproductive pool, may also enhance rates of infant morbidity and mortality, since the weaning diet is often lacking in protein and a variety of essential vitamins and minerals. Diets lacking in meat, fish, fowl, and dairy products are also deficient in vitamin B₁₂ which leads to pernicious anemia, neural disorders, psychotic behavior, and premenopausal infertility (Brasel 1978; Harris 1985; Horrobin 1971).

The disease burden of a population is another major factor which impacts demographic structure. While there is no evidence to suggest that the density dependant infectious pathogens which devastated Native American populations following European contact were present in the New World prior to A.D. 1492 (Crosby 1972; Cockburn 1971; Black 1975; Newman 1976), it would be highly misleading to describe the pre-Columbian Americas as a disease-free paradise (Dobyns 1983). Evidence derived from human coprolites (Horne 1985; Reinhard, Ambler, and McGuffie 1985), mummified soft tissue (Allison 1984), and skeletal remains (Buikstra 1981; Cohen and Armelagos 1984) demonstrates that prehistoric populations of the New World were subject to parasitic infections, malnutrition, and disease-related pathologies. However, since the number of material indicators which implicate specific disease organisms is quite limited (Goodman et al. 1984; Horne 1985), retrodictions of the specific disease

organisms present in any given region are difficult to evaluate. Nevertheless, it is possible to gain some appreciation of the relative importance of infectious disease in the Maya Lowlands and the potential impact of that disease burden on Maya demography.

Dunn (1968) suggests that complex ecosystems, such as tropical rainforests, support more species of parasitic and infectious organisms and more potential vector species and intermediate hosts than the simpler ecosystems of more temperate regions. The burden of disease on human populations, then, is greatest in the tropics (Neel 1982; Nutels 1968; Dunn 1968; Walsh 1984; Binford and Chasko 1976). Infectious pathogens, consequently, were probably an important element of the Maya ecosystem and a potential factor contributing to the collapse of Maya civilization (Shimkin 1973; Saul 1973).

Shimkin (1973) has suggested that the Maya may have faced a number of diseases, specifically endemic infections of American trypanosomiasis, *Ascaris*, and the enteropathogens which produce acute diarrheal illness. A number of human activities and environmental variables could have intensified the exposure of Maya populations to these disease organisms (Anderson and May 1982; R. Anderson 1982; Lycett 1985). Because many of the insect vectors of human pathogens specialize in the exploitation of disturbed environments, environmental changes resulting from agricultural intensification and settlement expansion would have increased the prevalence of pathogens and thereby the probability of infection. Furthermore, contact between vector species and human populations is maximized when other potential hosts are reduced in number (Speilman and Rossignol 1984). Thus, as the abundance of Lowland terrestrial fauna declined through habitat destruction and human predation, the probability of human infection by vector-borne diseases would have increased.

When parasites are endemic in an environment, as they are in the Maya Lowlands, infection is persistent. Newborn infants are partially and temporarily protected from disease by antibodies transferred from the mother before birth and via breast milk (Carpenter 1984). Subsequent development of immunity depends upon exposure to the pathogens present in the child's environment. Infections kill some children, possibly those with genetic, nutritional, immunological, or other deficiencies (Burnet and White 1972; Mata 1984); but by age three, most surviving children have acquired immunity to those pathogens which are common in their environment. Development of immunity is conditioned by both the relative abundance of a parasite and host population density. Thus, children in crowded, disease-ridden environments develop more antibodies at an earlier age (Fenner 1970; Burnet and White 1972; Carpenter 1984), and mortality is concentrated in the very young and the aged. Those age groups with the highest fertility rates are also those with the lowest mortality rates (Barclay 1958). If, however, childhood mortality is sufficiently high, disease may well regulate the size and growth rate of the population (Anderson and May 1979; May and Anderson 1979; May 1984; Kunstadter 1972; Chagnon and Melancon 1983).

Under these conditions, nutritional stress often becomes a major determinant

of the rate of infant mortality. The relationship between nutrition and infection is synergistic in that malnutrition exacerbates the severity of infections while infection aggravates nutritional deficiencies (Scrimshaw, Taylor, and Gordon 1968; Mata 1984). These conditions are more frequent and severe in pregnant women, infants, and young children. Because disease may severely reduce energy and protein absorption, infection-related malnutrition may occur even when the food supply is adequate. Chronic malnourishment diminishes immunological competence (R. Anderson 1981), and even mildly malnourished populations experience increases in chronic infections, the severity of disease, and mortality due to disease (Torun and Viteri 1984; Mata 1984; Keusch 1984). Our reconstruction of Late Classic Maya food production and procurement systems suggests a diet deficient in iron, zinc, niacin, and several amino acids necessary to protein synthesis. Immune deficiencies appear to be more frequent, diverse, and severe in individuals suffering from protein deprivation (Keusch 1984), but iron and zinc deficiencies also produce alterations in immunological function. Both parasitic infections and malnutrition may lead to an increase in nutrient depletion and, thus, intensify iron and zinc deficiencies (Baker and Jacobs 1984; Mata 1984; Solomons and Shripton 1984).

Late Classic Maya populations would have been subject to infection from a large number of parasitic organisms, the most devastating being a series of enteric pathogens which cause acute diarrheal illness. Such illnesses are currently the leading cause of childhood mortality in the developing world. Although *Escherichia coli* and rotaviruses are the most common agents, infection with a wide variety of bacterial, protozoan, and helminth species may produce acute diarrhea. High population density and poor sanitation conditions may increase exposure and, thus, the probability of infection. Under such conditions, children will develop multiple episodes of diarrhea in the first few years of life. While those who survive develop immunity to the majority of enteropathogens present in their environment, episodes of diarrheal illness contribute negatively to the nutritional status, growth, and development of the child (Carpenter 1984; Guerrant 1984).

In addition to enteric pathogens, populations of the Maya Lowlands would have been exposed to a variety of vector-borne microparasites, macroparasitic nematodes, and other infectious disease organisms. These organisms and the infections which they produce strongly influence and are, in turn, influenced by the nutritional status of the host. The results of this synergistic relationship include malnutrition, retardation in growth and development, and lowered immunological competence. Specific nutritional deficiencies of the Late Classic Maya diet would have exacerbated these problems. Mortality and morbidity levels among pregnant women and those in their child-bearing years, infants, and young children were probably very high. Furthermore, it is likely that the health status of the population as a whole was very low. As the interaction between malnutrition and infectious disease intensified, physiological stress would have increased, and rates of infant morbidity and mortality would have become progressively higher.

While disease and malnutrition would not have been responsible for the removal of the vast majority of the Maya, escalation of the trends discussed above may have resulted in a loss of reproductive potential sufficient to impair the capacity of Maya populations to replace themselves. High levels of juvenile mortality may have produced cyclical or even chaotic fluctuations in population size. This demographic instability would have been exacerbated as depleted cohorts attained reproductive maturity. Recovery from these short-term fluctuations would be expected, but only several generations after the initial perturbation.

Variability in demography, pathology, and nutritional status has consequences which may be detected in skeletal series. For example, increases in age- and sex-specific mortality should be reflected by dramatic rises in the proportion of all deaths that occurred in each cohort, and these changes in mortality schedules ought to covary with a reduction in the maximum stature attained by adults and with an increase in the frequency of nutritionally linked paleopathologies such as porotic hyperostosis and dental antimere asymmetry (Gilbert and Mielke 1985; Goodman et al. 1984; Perzigian 1977). Moreover, the stresses incurred ought to be chronic (rather than episodic), which should retard overall physiological development and limit the maximum stature attained (Nickens 1976).

This is in fact what the skeletal data from several Lowland Maya sites indicate. At Tikal a marked reduction in nonelite adult male stature is evident in the Late Classic (Haviland 1967), a pattern that also occurs at Altar de Sacrificios (Saul 1973), Barton Ramie (Willey et al. 1965), and perhaps Copan (Longyear 1952). At Tikal mortality was particularly high for infants and females entering child-bearing age (Haviland 1972), which also seems to have been the case at Copan in the Late Classic (Sanders, personal communication). At Altar de Sacrificios (Saul 1973) and Copan (Story, personal communication) the incidence of porotic hyperostosis increases markedly by Late Classic times. Porotic hyperostosis, most authorities now agree, occurs in populations suffering from chronic anemias, which are often caused by inadequate amounts of iron intake, although prolonged breast-feeding, diarrheal infections, and parasitic disease infestations may also play a role (Walker 1985). As we suggested above, iron deficiency was probably a major nutritional stress faced by the Classic Maya. Iron deficiencies would have become particularly severe if the Maya diet became increasingly maize dependent as population levels rose throughout the Classic. In addition, the incidence of linear dental enamel hypoplasia is fairly high for all time periods at Altar and Seibal, indicating that short-term developmental arrests from disease and/or inadequate nutrition were also a common problem (Saul 1973).

The data at hand therefore suggest that the Late Classic Maya may have had considerable difficulty maintaining demographic stability. It seems likely that this instability was largely the result of a collection of nutritional deficiencies synergistically linked to a variety of parasites which collectively placed progressively greater constraints on the number of individuals surviving to reproductive age. These problems, we believe, were mainly a function of the

high levels of basic staples consumed combined with the exceptionally low levels of meat intake.

Access to animal protein was a factor which also affected the demographic history of other parts of Mesoamerica. The population growth curve of the Basin of Mexico, for example, is logistic-like; growth was exponential during the Formative period, but population levels tapered off during the Classic (Santley and Rose 1979). Coincident with the decline of Teotihuacan, however, there was a rearrangement in population, not wholesale demographic loss (Sanders, Parsons, and Santley 1979). The demographic history of the Basin of Mexico is therefore quite different from that of the Maya Lowlands. This variability, we suggest, is related to differences in the respective resource bases which had a differential impact on the magnitude of the stresses involved. In the Middle Classic period, the frontier of Mesoamerican civilization lay directly to the north of the Basin. One property of frontier location is access to both local resources and those from areas beyond the frontier. This is especially the case when the frontier boundary is permeable, a characteristic which often defines the boundaries between states and unstratified sociocultural systems (Green and Perlman 1985). The region from which Teotihuacan and its dependencies derived faunal resources was thus probably considerably larger than the area occupied by the core Teotihuacan polity. Maya polities, in contrast, circumscribed one another, a situation which must have greatly constrained hunting ranges except in instances where one system was able to momentarily exercise hegemony over another. The spatial overlap of agricultural land and natural game preserves discussed above further acted to decrease game reserves and limit expansion of the Lowland Maya resource net.

The period of continuous growth during the Formative period in the Basin in Mexico is associated with comparatively longer life expectancy at birth (ca. 25 years) and a diverse diet relatively rich in meat (Sanders, Parsons, and Santley 1979). Although the paleopathological status of the inhabitants of Teotihuacan has yet to be defined in detail, there is reason to believe that the slowdown in growth rates in the Classic was in part a function of disease and nutritional stress (Santley and Rose 1979). According to Goodman et al (1984:17), "age at death stands as perhaps the most important single indicator of stress." At the Tlajinga 33 apartment complex at Teotihuacan, life expectancy at birth was 13.5–16.5 years (Sanders et al. 1982; Storey 1983, 1985). This contrasts markedly with the pooled estimate for El Arbolillo, Ticoman, and Zacatenco, which suggests significantly longer lifespans (Santley 1977). The Tlajinga 33 compound was occupied by persons who had a relatively low socioeconomic position, which is reflected by their reliance on adobe architecture and by a very impoverished faunal assemblage (Widmer, personal communication). While Storey (1983, 1985) has suggested that immigration from the countryside was the primary mechanism which kept the city demographically alive, the establishment of many rural sites throughout the Basin of Mexico in the Middle Classic indicates that a substantial amount of migration in the other direction also occurred during Tlamimilolpa times. The migration of young adults from compounds like Tlajinga 33 and La Ventilla would result in their removal from

skeletal populations interred in the city, making life expectancy at birth seem very low. Thus, while disease and malnutrition may have had great impact on the demographic stability of certain components of the Teotihuacan settlement system, the total amount of such stress affecting the polity as a whole was probably much more moderate, at least in comparison with the Maya Lowlands.

Although growth curves vary from region to region in the southern Maya Lowlands, population levels generally peak in the Late Classic (Figure 2), with many areas subsequently undergoing a catastrophic demographic crash (Culbert n.d.; Culbert and Kosakowsky 1985; Fry 1985; Rice and Rice 1985). As we have pointed out, the landscape in which these demographic collapses occurred was one in which meat and alternative sources of high-quality protein were almost entirely lacking. Although elite nutrition was undoubtedly somewhat better (as indicated by taller adult stature), all components of Maya society were probably hard pressed by the end of the Late Classic. The reduction in mean stature in the Classic strongly suggests that Maya populations were exposed to increasingly more severe stress. We suspect that the diet available to the average Maya peasant throughout most sections of the Lowlands was worse than that of the average urban dweller at Teotihuacan. Life expectancy at birth, then, should have dropped markedly as the diet became progressively poorer. Ultimately, age-specific mortality rates may have increased to the point where parents would have had great difficulty raising children to maturity, and because all parts of the Maya landscape were experiencing the same set of

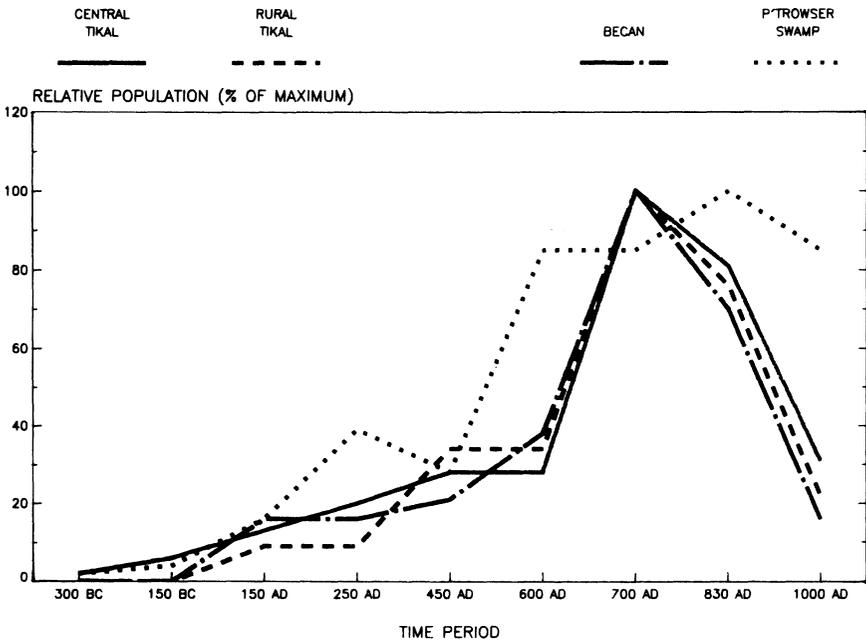


Figure 2. Population through Time at selected Lowland Maya Sites

problems, the size of the population as a whole began to decline. We suggest that this process began sometime during the eighth century A.D., if not slightly earlier, and was well under way by the beginning of the ninth century.

Degradation of the Agricultural Landscape

We believe that Late Classic Maya populations made critical short-term decisions to reorganize land use strategies in the face of demographic loss and declining yields from slopeland cultivation. These decisions had long-term effects on the viability of the agricultural resource base. In order to model the system failure, first let us assume that, in response to rises in population density, most parts of the Maya environment were intensively exploited. This intensification resulted in the almost wholesale removal of the climax forest and many successional species from vast sections of the interior Lowlands. Kitchen gardens, planted in a variety of economically useful species and enriched with night soil and organic household refuse, were placed next to residences. Slopelands were brought under short-fallow agriculture and/or annual cropping, were planted mainly in staples (probably maize), and were terraced to retard erosion and other soil degradation processes. Wherever possible, lakeshores and bajo margins were converted to raised fields which were planted in maize and dietary supplements. Second, let us assume that kitchen gardens and raised fields produced high yields, while production levels on terraced slopelands were substantially lower. This variability in production was primarily a function of soil enrichment practices which were only feasible at localities where sources of organic fertilizer were close at hand. Finally, let us assume that, when inadequate labor is available to maintain all components of the agricultural system, farmers would drop less productive strategies and favor those components that produce significant returns (Lycett 1984). If the amount of labor expended in different strategies is equal, the strategy that will be maintained is the one that is the most efficient, that is, that produces the greater yield. Least effort strategies will only come into play if desired returns can be obtained with different labor inputs, yet productivity does not vary that much relative to the subsistence household's perceived needs.

Intensively cultivated agrarian landscapes of the type just discussed can only be maintained by the input of substantial amounts of energy to check degradation and plant successional processes. In such systems there is a close articulation between different parts. For example, the viability of raised field agriculture is in part contingent on slopeland terracing to inhibit erosion once large areas of forest have been cleared. The agrotechnology which supported Classic Maya civilization was human-powered, and vast amounts of labor were required to maintain the agrarian system. Any factors which limited or constrained the application of labor could thus have had severe repercussions on the viability of the agricultural support base as a whole. As already pointed out, it seems likely that the Maya had severe problems raising children to adulthood by Late Classic times. These problems were a function of chronic malnutrition and increased susceptibility to disease, which aggravated rates of

mortality, periodically decreasing the numbers of producers. Chronically malnourished individuals are also less able to maintain high work loads, which places further constraints on the productive capability of the system. In our opinion, toward the end of the Late Classic the Maya economy was severely strained because it lacked adequate power to maintain the structure of the subsistence system. Power shortages of this sort must be dealt with immediately. Short-term solutions must be found, and they must have involved cutbacks in the amount of labor devoted to slopeland agriculture, that segment of the agrarian support base which was the most unproductive and inefficient. Short-term solutions, however, often have long-term consequences which threaten the viability of the entire productive base.

It is conceivable, then, that the Late Classic collapse was the direct result of farmers making economically rational short-term decisions which were dysfunctional on a long-term basis. Reductions in the area of slopeland cultivation would have exposed large portions of the landscape to the effects of those very degradation processes which terracing was designed to retard. One thing we know about terrace systems is that they require continual maintenance. Lack of maintenance commonly results in breaches in the terrace wall, and once a break occurs, the erosion of soil from behind the embankment is rapid and assured. Often as well, the smallest terraces are located upslope, due to the increase in slope angle, and these typically are the first to be abandoned because more work is required per unit of cultivated space to maintain their embankment walls. Inadequate maintenance upslope will thus undermine the viability of components of the terrace system downslope. The erosion of slopelands will greatly accelerate rates of sedimentation in bajos and lakes. Increased sedimentation clogs canals which drain raised fields, ultimately raising the water table as well as reducing the biological productivity of microflora used as mulch. These processes would have had the effect of decreasing the area devoted to raised field agriculture, as well as of limiting the productivity of those fields which were still under cultivation. The erosion of topsoil from slopelands would have also impeded patterns of plant succession, thus impairing forest regrowth. Seral development generally occurs quite rapidly in the humid tropics, with dense woodland (but not climax) vegetation returning within twenty years. Succession rates, however, may be significantly retarded if edaphic conditions are greatly altered by habitat destruction. The restriction of many species of seral and climax vegetation to refuge habitats on the margins of cultivated zones would have further slowed forest regrowth. It may consequently have taken decades, if not longer, for normal patterns of seral development to become firmly established. Thus, what was formerly a productive agrarian landscape may have been quickly transformed into an agricultural wasteland, so to speak, once sufficient labor was no longer available to drive the subsistence economy.

A common response to acute degradation and catastrophe is migration of segments of the population to new areas and reorganization of the local subsistence system by the population that remains. This appears to have occurred

in the Basin of Mexico, where populations moved to the Teotihuacan Valley following the eruption of the volcano Xitle which devastated the southern Basin in Tzacualli times (Sanders, Parsons, and Santley 1979). Likewise, alkalization appears to have been the primary factor effecting the abandonment of southern Mesopotamia, the heartland of Sumerian civilization, in the Early Dynastic period (R.M. Adams 1981). A major abandonment process may have also occurred in the Maya region. For example, there is evidence of population growth in a number of regions nearer the coast coincident with or immediately following the collapse in the South, thus implying emigration of populations from the interior (Andrews and Sabloff 1986; Sabloff 1977). At the same time, evidence exists for population persistence in the South as well as some regrowth in the Postclassic (Chase and Rice 1985; Culbert 1973).

Absence of Macroregional Resource Extraction Networks

The establishment of macroregional resource-extraction structures is another common response to stresses on the local economic base. Before the industrial revolution, rulers of petty states often waged wars of conquest to acquire tributary domains. These tributary systems concentrated goods in the heart of the empire, with the provincial citizenry rarely receiving anything in return. In highland Mesoamerica, imperial regimes extracted both subsistence and luxury goods. For example, during the Late Aztec period, exotic items from throughout the empire were redistributed to the ruler's clients and dissatisfied lesser nobles in order to solidify the paramount's political position. In contrast, subsistence goods, extracted primarily from nearby provinces, were used to support the royal palace and subsidize state building projects or were stored for allocation to the populace at large in times of need (Bedoian 1973; Berdan 1982; Santley 1985). Although large quantities of foodstuffs (or their equivalents) were consumed during transport to Tenochtitlan, the total amount of subsistence goods that entered the Aztec capital was still staggering. Most of this tribute in foodstuffs was provided by the peasant farmer. High levies could be extracted from the peasantry in Central Mexico because farmers were able to produce substantial surpluses without the danger of agricultural intensification degrading the landscape. The surpluses, in turn, made the support of large numbers of craftsmen and other specialists economically feasible (Sanders and Santley 1983), and the Aztecs used their control of macroregional extraction nets to make other centers in Central Mexico dependent on craft goods produced in Tenochtitlan (Hassig 1985). Aztec control of this tribute system therefore enhanced the security of the core of the Aztec Empire, Tenochtitlan and its immediate allies, by providing their populations with a resource base which other centers lacked.

Such was not the case in the core of the Maya Lowlands. Here, the establishment of tributary domains would not have solved the problem of subsistence stress because the productivity of the agricultural system declined with intensification. It is quite likely, then, that by Late Classic times virtually all of the goods produced by the farmer were consumed in his household. Levies exacted

to subsidize the state probably declined on a per capita basis throughout the Classic period, but state institutions persisted because population growth provided more producers, each of which, however, now contributed a smaller portion of their household budget to support the organizational hierarchy. The inability to produce even small surpluses which could be "reinvested" in system structure may be the reason why Maya political organization was decentralized and why basic producers were dispersed across the landscape near agricultural land. It may also explain why craft specialization was so underdeveloped among the Late Classic Maya.

Although subsistence goods could have been obtained from populations in the peripheries, the high costs of overland transport would have greatly limited the amount of tribute that ultimately arrived in the core of the Lowlands. In contrast, large peripheral Maya centers such as Copan and Palenque were more optimally situated. Here, water transport or proximity to less densely settled areas may have facilitated increases in system scale. Areas such as central Honduras and the south Gulf Coast, then, may have been dominated by large polities located near the frontiers of the Maya region. Archaeological evidence, however, suggests that the western periphery was densely settled throughout the Classic (Coe 1965; Santley et al. 1984). The presence of such major Gulf Coast polities would have placed severe constraints on Maya expansion into Tabasco and southern Veracruz. The eastern periphery, on the other hand, was never as densely settled as the Maya Lowlands or the Gulf Coast, though population levels did peak in the Late Classic (Healy 1984). In addition, a number of large sites are fortified, implying warfare between centers. Maya centers in western Honduras consequently could have extracted relatively large amounts of tribute from polities on the eastern periphery; however, large parts of Honduras also experienced substantial demographic loss at the end of the Classic period (Healy 1984). Expansion in this direction thus would not have solved the problem of provisioning major Maya centers on a long-term basis.

Therefore, any attempt by a Maya polity to carve out a tributary domain throughout much of the southern Lowlands would have seriously undermined the economic variability of the conquered state, and what little tribute may have been extracted would have been literally eaten up during transport back to the fledgling capital. In fact, attempts to found tributary domains by major Maya centers such as Tikal, Calakmul, Copan, or Palenque may well have accelerated the collapse. Warfare had certainly reached endemic proportions by the Late Classic period, suggesting that the rulers of major states were trying to impose levies on their neighbors. Empire formation, however, was precluded over the long run because food producers were unable to defray the costs involved. Likewise, it appears that the burden of supporting local state infrastructures had become too much for the peasant to bear by the end of the Late Classic (Lowe 1985). This, combined with the diminishing returns from the degraded agricultural environment, led first to the disintegration of political authority, then to further instability, and ultimately to abandonment.

SUMMARY AND CONCLUSION

In a recent comprehensive study of the collapse, John Lowe (1985) attributes the abandonment of major Maya centers primarily to the disintegration of political structure. However, the Maya collapse involved more than the simple breakdown of a hierarchical political organization; it also involved a systemic failure in which substantial portions of the southern Lowlands were almost completely abandoned, not to be reoccupied until comparatively recently. Likewise, we take issue with Lowe's (1985:202) claim that, once the area was abandoned, "raiding and population flux acted to inhibit [the] recovery of sites whose sociopolitical organization had previously disintegrated." While episodes of political balkanization can and do effect changes in population distributions, never do they cause such extensive and long-term abandonment. What we would expect, if the disintegration of administrative authority was the primary cause of the collapse, is a reorganization in system structure, not the abandonment of the area by elites and commoners alike. Therefore, unexplained in Lowe's model, or schemes like it, is why the disintegration in hierarchical political organization was accompanied by wholesale population loss.

In this paper we have tried to sketch an explanatory framework to account for the processes of both demographic loss and site abandonment. Many of the variables to which we have assigned causal priority have been in the literature for years (Cooke 1931; Morley 1946; Sabloff 1971; Sanders 1962, 1963); however, taking another look at the collapse has allowed us to cast them in a new light. It is our position that the high population densities attained throughout much of the southern Lowlands in the Late Classic period were fundamentally unstable. The Late Classic Maya had considerable difficulty raising children to reproductive age, because of an interrelated series of nutritional problems synergistically linked to an increased disease burden. Demographic difficulties probably caused fluctuations in population levels, with decreases in the number of food producers occurring at the same time as massive amounts of labor were required to maintain the agricultural ecosystem. The viability of that agricultural system was contingent on the simultaneous use of both slopelands and wetlands. Cutbacks in the extent of terraced slopelands in use, due to declines in food producer numbers and enhanced degradation from monocropping, would have threatened the viability of the entire subsistence base as well as retarded normal rates of plant succession. Put simply, Maya centers were abandoned, not because of burgeoning managerial costs, peasant revolts, or invasions from the outside, but because of erosion of the system's economic base.

Tropical rainforests are fragile environments. They can support dense populations, but only if land-use regimes maintain a multitiered agroecosystem or major inputs of matter and energy come from outside sources. Even the use of mechanized equipment and the application of vast amounts of chemical fertilizer may be insufficient to check degradation processes once the landscape is monocropped on an annual basis. Substantial parts of the southern Lowlands

are currently being recolonized by farming populations. Due to government incentives, farmers from densely settled regions in the Mexican and Guatemalan highlands are opening up large tracts of lowland forest for cultivation. In the Lacandon forest, for example, the farming strategies being applied are ones which have proven successful in parts of Mexico where monocropping has little impact on accelerating degradation processes (Wilkerson 1985). These strategies are having devastating consequences on the viability of the natural Lowland ecosystem. Land surfaces are being baked solid after several years of monocropping, and erosion is removing what little soil is left, effectively precluding both human utilization and the return of the forest. Mismanagement of the Lowlands today is producing the same consequences with which we feel the Late Classic Maya had to deal. Areas such as the Lacandon forest and the Peten constitute natural laboratories where archaeologists and developmental planners alike can study the effects of intensification on the viability of agricultural systems. Hopefully, this is the direction that future work on the collapse will take.

NOTE

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