Mayan Urbanism: Impact on a Tropical Karst Environment

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Summary. From the first millennium B.C. through the 9th-century A.D. Classic Maya collapse, nonurban populations grew exponentially, doubling every 408 years, in the twin-lake (Yaxha-Sacnab) basin that contained the Classic urban center of Yaxha. Pollen data show that forests were essentially cleared by Early Classic time. Sharply accelerated slopewash and colluviation, amplified in the Yaxha subbasin by urban construction, transferred nutrients plus calcareous, silty clay to both lakes. Except for the urban silt, colluvium appearing as lake sediments has a mean total phosphorus concentration close to that of basin soils. From this fact, from abundance and distribution of soil phosphorus, and from continuing post-Maya influxes (80 to 86 milligrams of phosphorus per square meter each year), which have no other apparent source, we conclude that riparian soils are anthrosols and that the mechanism of long-term phosphorus loading in lakes is mass transport of soil. Per capita deliveries of phosphorus match physiological outputs, approximately 0.5 kilogram of phosphorus per capita per year. Smaller apparent deliveries reflect the nonphosphatic composition of urban silt; larger societal outputs, expressing excess phosphorus from deforestation and from food waste and mortuary disposal, are probable but cannot be evaluated from our data. Eutrophication is not demonstrable and was probably impeded, even in less-impacted lakes, by suspended Maya silt. Environmental strain, the product of accelerating agroengineering demand and sequestering of nutrients in colluvium, developed too slowly to act as a servomechanism, damping population growth, at least until Late Classic time.

Alone among the world's high civilizations, past and present, that of the Maya arose in lowland tropical forest and flourished in that productive (*1*) but ostensibly fragile environment (*2*) for many centuries. Settled agriculturists, reported from the wider Maya area from the third millennium B.C. (*3*), were established in the lake district of the endorheic central Peten, in northern Guatemala, by approximately 1000 B.C. (*4*). By Late Preclassic time (250 B.C. to A.D. 250), as the specifically Mayan urban settlement (*5*) took shape, much of the central area was deforested (*6*). During Classic florescence, A.D. 250 to 850, when the population of the Maya Lowlands was at least 5 million (*7, 8*), Tikal and several dozen less important centers were built and repeatedly rededicated in the 20,000-square-kilometer core region (*9-11*). Except for some Postclassic (10th- through 16th-century) recolonization (*12*) and some 20th-century resettlement, both mainly confined to the immediate vicinity of the larger lakes (Fig. 1), the Peten has remained almost uninhabited since the 9th-century Classic collapse.

A lively extraregional commerce, involving exchange with Classic Teotihuacan and other distant centers, is archeologically documented for the early Maya state (*13-15*). External economic and political interference may therefore have contributed to the collapse (*16*). More generally, accepting the supposed vulnerability of tropical forest (*2, 11, 17*) to agricultural and especially to urban disturbance, some Mayanists (*7, 16, 18*) believe the culture to have grown past metastability by Late Classic time and to have abandoned the core area in consequence of severe environmental strain. Unfortunately, in the absence of quantitative information on Mayan subsistence, metastability, like its components overexploitation and environmental strain, is easy to postulate but difficult to measure or disprove.

We now report the results of paleoecological research in the Peten lake district directed at the problem of measuring environmental strain. Two similar and adjacent closed lake basins were chosen for limnological, archeological, and sedimentological study, because one (Lake Yaxha—maximum depth, 27 meters) was known to have been heavily urbanized in Classic and Postclassic times, whereas the other (Lake Sacnab—maximum depth, 13 m) was more lightly occupied (*12, 19*) and proves to have held no Postclassic habitation (*20*). At Lake Petenxil (maximum depth, 4 m), on the edge of the savanna south of Lake Peten Itza, the investigations of Cowgill and Hutchinson (*21*) had yielded evidence of Mayan disturbance from the inception of the stratigraphic record, ^{14}C-dated at approximately 2000 B.C. In the longer (9000-year) perspective given by our palynological results (*22-24*) from Lake Quexil (maximum depth, 32 m), 2 km from Petenxil, the episode of deforestation and lacustrine siltation appears as a 25- to 30-century interruption, from about 1500 B.C. to A.D. 1550, in a pollen record otherwise dominated by dense tropical forest. In Lake Yaxha, where borings failed to penetrate the thick layer of silty clay that floors the lake, our section begins about 50 B.C. in the Late Preclassic, but a complete record of the Maya episode is found in sediments of Lake Sacnab. Pursuing our principal objective, "to evaluate the basin-wide budgets of water, carbon, and major cations and anions at the present time and as they were modified by Maya exploitation" (*25*), we shall examine changing nutrient (phosphorus) budgets in the two differently impacted lakes, and compare them with that of less-impacted Lake Quexil.

Economic Geography

The central Peten is a low-lying (altitude 100 to 300 m), steeply dissected karst plateau, developed on Cretaceous and Tertiary limestones, which are locally dolomitic and interbedded with gypsum; no volcanic rocks occur (*26*). Solu-

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tion (sinkhole, haystack-hill) topography is given an east-west linearity by a system of en echelon faults. Rainfall averages 1601 mm, 90 to 95 percent of which falls between June and December (*27*). The lake district (Fig. 1) is a chain of closed basins elongated in an east-west direction, several of which have deep, parallel-aligned troughs at the feet of south-facing fault scarps, following the main graben system along latitude 17°N. Other topographic depressions are occupied by swampy, clay-floored *bajos*, some of which hold shallow lakes in the rainy season (*28–30*); others, on reportedly lateritic soils (*31*) west and south of the lakes, by anomalous savannas (*32*), often presumed to result from Mayan deforestation (*33, 34*).

A complex pattern of extreme soil variation (*29–31*), resulting from downwasting of limestone uplands and colluviation of *bajos*, makes it difficult to judge either the pre-Maya or the present-day agricultural potential of the region as a whole (*7, 11, 20, 35*). Modern vegetation (*32–34, 36*) is also remarkably variable, even within the apparently homogeneous forest north and east of the savannas; the intricate pattern of infrared reflectance, computer-enhanced from Landsat imagery, is conformal with forest types as mapped on the ground in the Yaxha district (*32*).

In the humid, riverless environment of the core area, where midden refuse is deficient in plant remains (*37*), and irrigation canals [known, with terraces, in riverine plains elsewhere in the Maya Lowlands (*11, 38, 39*)] would have served no purpose, neither the crops nor the agronomic technology have left undisputed archeological traces. Shifting (*milpa*, swidden) cultivation of maize, however adequate for 17th-century (*40*) and modern (*35*) descendants of the Postclassic peasantry, is demonstrably inadequate for large and exponentially growing populations (*11, 41*). Despite the lack of field evidence, we have argued elsewhere (*20*) that Classic agronomy in the Peten must have been intensive, that is, with a short fallow cycle, but locally diversified [with mixed root and field crops, plus arboriculture and aquaculture (*38, 42*)] as dictated by widely varying topography, geochemistry, natural vegetation, and soils. Raised fields [*chinampas* (*11, 30, 38, 43*)] may have clustered around *bajos*, as they do in Belize (*43*), but, after the massive siltation that we have observed in lakes, fossil *chinampas* are unlikely to crop out above colluvium.

Overexploitation and environmental strain can be rephrased as accelerated demand and diminishing supply. From our paleoecological studies, which included estimates of population density (*20, 44*) and of the area disturbed by residential construction, we infer accelerated subsistence demand from evidence of exponential population growth (Fig. 2). Nonsubsistence (engineering) demand is correlated in part with residential construction and thus with population size, but separate volumetric estimates for residential and for urban construction are not yet possible. As total agricultural yields cannot be estimated even roughly, and as significant amounts of food may have been imported, nothing quantitative can be said about subsistence supply. The economist's customary inference, that its instantaneous per capita rate must have equaled that of demand, is circular if the economy was metastable.

Environmental strain is not a rate, however, but a condition; it develops as an altered state of an ecosystem after continued stresses (demands) perturb outputs (rates of supply) of certain materials. Under any agricultural system, supply of soil- and waterborne plant nutrients (nitrogen, sulfur, and phosphorus) is deflected to human nutrition. If the tropical forest is peculiarly vulnerable to agricultural stresses, one underlying mechanism must be inadvertent sequestering or downstream export of the same nutrients after nutrient-poor soils are leached under heavy rainfall. Phosphorus is the element most likely to have become deficient in the Mayan environment, as soluble phosphorus is immobilized by calcium in limestone terrain, and as losses by leaching and by harvesting, unlike those of nitrogen and sulfur, are not replaced from the atmosphere (*45*).

As long as nonsubsistence demands are mainly for clothing, ceramics, and residential shelter, subsistence stress on nutrient supply can usually be minimized by prudent agronomy. Except perhaps for acceptable carving stone and (in Classic time) for timber, the Peten has sufficient nonferrous materials for urban construction. With urbanization, we believe, the ecological consequence of engineering demand was interference with agricultural production, that is, with subsistence supply. Direct substitution of urban construction for soil of good quality is observable at Yaxha, as at many urban centers, but our limnological data imply a more insidious form of strain: depletion of nutrients from unurbanized sites by accelerated erosion and slopewash. Whether strain was a sufficient cause of the collapse throughout the Peten cannot be decided from a single limited study, but the strain on Yaxha's resources was undoubtedly severe.

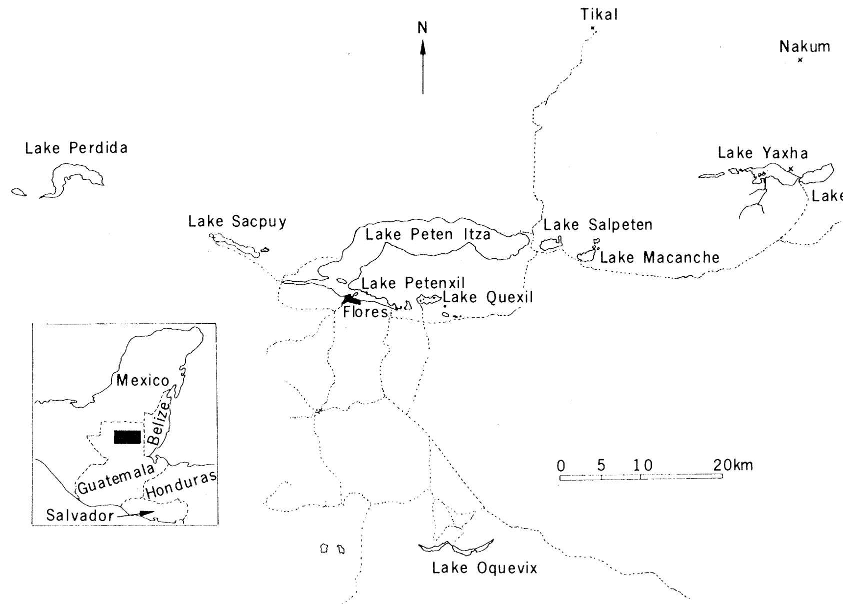

Fig. 1. Map of the Peten lake district, based on Landsat infrared imagery.

Populations and Residences

Ten archeological transects, each 500 m wide, were surveyed and mapped in the Yaxha-Sacnab basin in the dry season of 1974 (Fig. 3). Except that equal numbers of transects (operations 1 to 5 and 6 to 11) were required to extend north and south from the lake shores normal to the topographic trend and in numbers proportional to shoreline length (6:4), their positions on the east-west axis of the combined basin were randomized. Transects were carefully searched (but not cleared) by D.S.R., P.M.R., and

Table 1. Time-specific estimates of population density (*79*) and nonurban disturbed areas (*80*) on transects within the two subbasins. Population densities are maxima attained by the end of each archeological period. Disturbed areas, assumed to have been subject to erosion long after abandonment, are not only maximal for each period but cumulative over previous periods.

Archeological period	Duration (years)	Population			House and group area on transects (m^2/km^2)	Disturbed area of 200-m basin [m^2/$km^2_{(lake)}$]
		Maximum density per km^2 on transects	Mean on 200-m basin per $km^2_{(lake)}$	Mean on 2-km basin per $km^2_{(lake)}$		
Lake Yaxha, area 7.4 km²; land area below 200 m, 8.31 km²						
Late and Postclassic	1130	256	75.27	244.0	15967	17930
Early Classic	300	101	98.20	319.0	7824	8786
Late Preclassic	500	70	52.19	173.0	4136	4644
Middle Preclassic	750	22	13.71	67.7	1182	1327
Lake Sacnab, area 3.897 km²; land area below 200 m, 21.74 km²						
Late and Postclassic	1130	168	237.17	167.6	10406	58051
Early Classic	300	102	410.00	239.5	5723	31927
Late Preclassic	500	51	224.00	128.3	3382	18867
Middle Preclassic	750	34	110.67	85.5	1561	8708

trained assistants for a distance of 2 km, or farther if more distant house-mounds were encountered. The island site of Topoxte (*12*) was also searched (operation 6). Of 860 mounds found on and off transects and within the settlement of Topoxte, 586 lay within the transect areas, which sampled about 25 percent of the 40 km^2 thought before the survey to constitute the hydrologic basin. On southern shores, all mounds lay within, mostly well within, the mapped 200-m contour, which encloses both lakes about 21 m above their 1974 level (*27*, *46*). On northern shores, most mounds lay between 220 and 280 m (Yaxha) or between 200 and 260 m (Sacnab), and these also are considered riparian. For calculations in this article, a few residences beyond the divide to the north (*47*), outside the 5.288 (Yaxha) and 3.348 (Sacnab) km^2 of surveyed basin area, were excluded. The sampling design also required that a randomly chosen 210 structures (approximately one-quarter of the total) be test-pitted and dated to one of four precollapse periods by ceramic content. Sharper chronological resolutions, feasible if test-pitting had been followed by complete excavation, was sacrificed to provide a geographically extensive data base. Archeological results, including descriptions of diagnostic ceramic types, have been published or are in press (*20*, *48*, *49*).

To measure human influences on the lakes, it is necessary to extend mean population densities and intensities of disturbance on transects to some definite riparian fraction of each subbasin (*47*). We chose first the mapped basin area below 200 m (Table 1, column 4), 72 percent of which surrounds Lake Sacnab (Fig. 3), and divided extrapolated population sizes by the area of each lake. As a proximal basin of 41.35 km^2 total area (30.05 km^2 land area) with mean lakeward slope 2.5 percent, this area seems reasonable as a source of soil movements and runoff, but it omits many mounds found near northern shores and assigns too much archeologically unknown land to Lake Sacnab.

We therefore tested an alternative assumption: Table 1, column 5, shows time-averaged and lake-area-specific populations on land areas drawn by connecting distal ends of transects, 2 km from lake shores (38.92 km^2, of which 32 percent surrounds Lake Sacnab). The procedure reverses relative population sizes for the two subbasins, making them at maximum 6780 and 2090 instead of 2130 and 3650 for Yaxha and Sacnab, respectively, while Lake Yaxha's land : water ratio, relative to Lake Sacnab's, becomes 1.2:1 instead of 1:5. Our sampling methodology, designed to evaluate large population changes over time, cannot resolve small spatial differences, either within or between subbasins. If all populations are riparian, as these are, populations of roughly equal size and density should have more influence on the smaller of two lakes; but, whereas the 200-m basin probably exaggerates the potential human impact on Lake Sacnab, the 2-km basin rather clearly exaggerates the influence of Yaxha's nonurban population.

In further treatment, therefore, we disregarded between-lake differences in population, to concentrate on basin-wide changes in time-specific impact. Time-averaged and lake-area-specific intensities of nonurban disturbance as shown for the 200-m basin (Table 1, column 7) were used only to compute virtual transfers of phosphorus (Table 2). Disturbed areas plotted in Fig. 2 are time-specific data (Table 1, column 6).

Just before the collapse, when residential and other nonurban disturbance in the Yaxha subbasin affected 13 to 42 hectares, depending on the basin area assumed, the area of urban Yaxha was about as large—34.4 ha. Postclassic Topoxte, a more compact center built by a much smaller population confined to the western end of Lake Yaxha, covered only 4.6 ha. Volumes of tall Mayan structures are poorly known and are not so

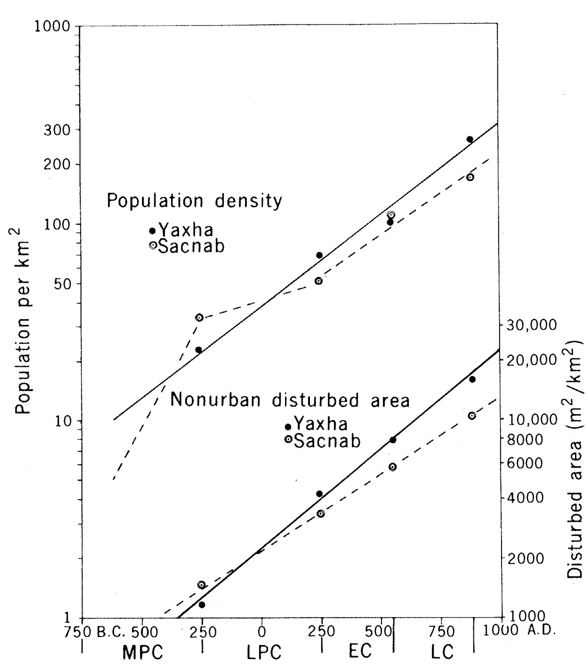

Fig. 2. Estimated population density and cumulative nonurban disturbed area in the Yaxha and Sacnab subbasins. Abbreviations: *MPC*, Middle Preclassic (750 to 250 B.C.); *LPC*, Late Preclassic (250 B.C. to A.D. 250); *EC*, Early Classic (A.D. 250 to 550); *LC*, Late Classic (A.D. 550 to 880). Points are plotted at the ends of periods by convention.

closely related to their ground areas as are those of houses (50). We call attention to urban influence on Classic siltation rates in Lake Yaxha (Table 3 and Fig. 4), but attempt no quantitative comparison of urban and nonurban disturbance.

Exponential population growth, often taken as axiomatic where "formative" cultures became "classic" civilizations, is not often documented as convincingly as at Yaxha and Sacnab (Fig. 2). When data are plotted semilogarithmically (and fitted by eye, precise curve-fitting being unwarranted), population densities and nonurban disturbance increased at closely similar rates in the Yaxha subbasin and at similar but somewhat lower rates near Lake Sacnab. The ensuing collapse to Preclassic densities (20, 44), not shown in Fig. 2, is mathematically similar to a relaxation oscillation. This mode of plotting obscures some interesting points that emerge in closer study of Table 1:

1) The nonurban population of the Yaxha subbasin was generally larger than that of the Sacnab subbasin; its density became very high (approximately 250 persons per square kilometer) in Late Classic time.

2) According to Rice (48), the Middle Preclassic population grew more rapidly around Lake Sacnab. A slight but significant lag in Sacnab's growth rate allowed Yaxha's population to surpass it during Late Preclassic time.

3) Population growth in the entire basin was steady over some 17 centuries, a remarkably long "logarithmic phase" for any population. Nevertheless, the rate of increase, about 0.17 percent per year, was far from explosive; the doubling time at this rate is 408 years, or 12 to 16 generations. If such growth was typical of the Maya area, it must have looked like equilibrium to the oldest inhabitants. However visible in historic perspective, Mayan overpopulation and metastability were probably not perceptible to the managerial elite (15) or their economic advisors.

Table 2. Delivery rates (apparent outputs) and transfers of phosphorus to lakes Yaxha and Sacnab from riparian populations and nonurban disturbed areas, projected to the 200-m contour.

Period	Apparent output (kg per capita per year)		Virtual transfer in disturbed soil (percent per year)	
	Yaxha	Sacnab	Yaxha	Sacnab
Post-Maya*			0.8	0.9
Late and Postclassic	1.46	0.40	4.0	1.1
Early Classic	0.33	0.55	2.4	4.6
Late Preclassic	0.25	0.61	1.8	4.7
Middle Preclassic		0.28		2.4

*Post-Maya phosphorus influxes continued at rates equivalent to an output of 78 to 84 percent of Late plus Postclassic populations. Areas of Yaxha and Topoxte (urban) sites are entered as disturbed during post-Maya time only.

Stratigraphy and Sediment Chemistry

Sediment sections obtained with a piston-corer (Livingstone) in lakes Quexil, Sacnab, and Yaxha are summarized in Figs. 4 and 5. Attempts at close-interval dating and evaluation of sedimentation rates encountered interesting difficulties (23, 51). Maya-influenced zones in cores are thick deposits of silty, montmorillonitic clay (52), the insoluble residue of the country rock (an impure limestone) after solution-downwasting and soil formation (53). As a rapidly deposited, allochthonous lake deposit, the material is poor in datable carbon and inimical to good preservation of fossils, including some pollen grains. Especially in hyperconical (trumpet-shaped) lake basins with sinkholes and deep trenches, such as Lake Yaxha, sediments subject to horizontal transport and focusing (54) give seriously distorted measurements of vertical accumulation. Our sediment-trap measurements (51) have been rejected for this reason. Moreover, as is usual in limestone terrain, ^{14}C dates of lacustrine materials show large errors, probably varying over time with the effectiveness of the Maya clay as an aquiclude (55) and resulting from the "hard-water-lake effect" (56). Pending further study, we disregarded all ^{14}C dates except the oldest [DAL 198, 8410 ± 180, Dalhousie II (57)], which was of a sample of lake-deposited wood, and subdivided all sections on the basis of their pollen stratigraphy.

Details of pollen sequences in the Sacnab and Quexil cores are to be presented elsewhere (24). Relatively large amounts of unidentifiable, probably rebedded pollen in the Yaxha core permit interpretation of its lowest 6.35 m as Maya clay, within which a 2.3-m zone strongly dominated by pollen of Compositae implies the culmination of agricultural weeds in the Early Classic. Degraded pollen is less troublesome in clay zones

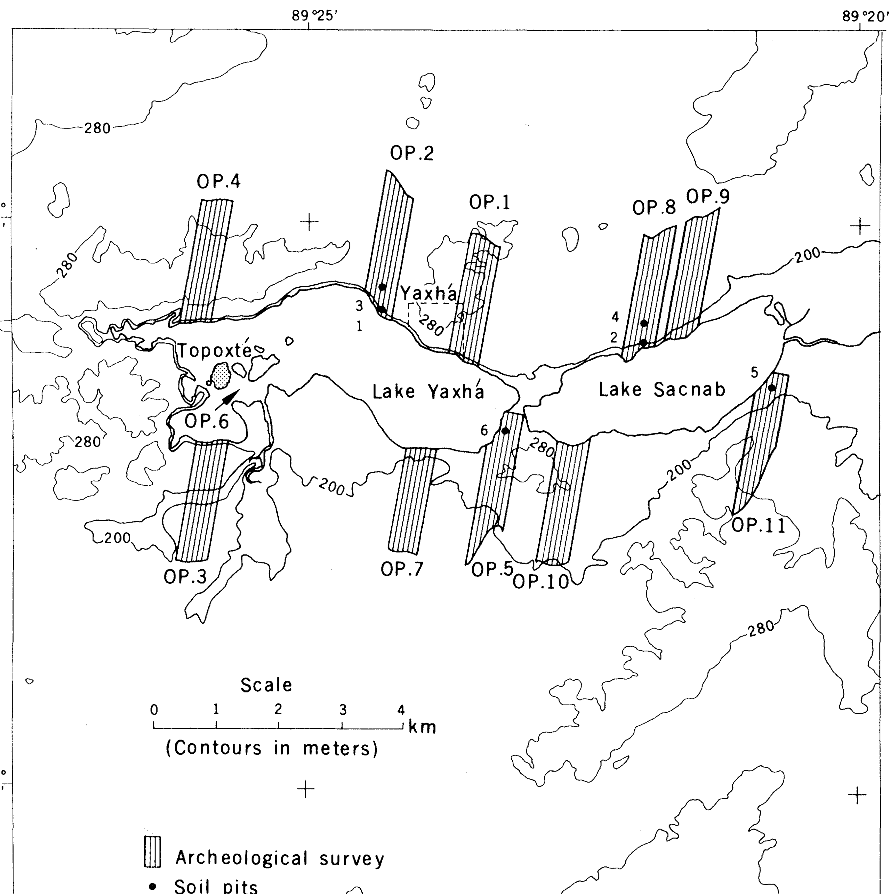

Fig. 3. Archeological sampling transects with locations of soil pits (*OP* for *operación*).

of other cores. Major features of all available pollen diagrams, from the Maya Highlands (*58*) as well as from Lake Petenxil (*6*), are imposed by human disturbance of vegetation, not by climatic changes. Correlation of sequences of the principal pollen types is therefore fairly secure, and archeological dating, at the wide intervals adopted in this paper, is believed to be accurate within a century or two.

As compared with Tsukada's Petenxil sequences (*6*) (for which ^{14}C dates are uncorrected for hard-water-lake errors), the pre-Maya high-forest pollen zone of the Quexil core is the oldest lowland lake deposit yet known in Central America. Above this zone, below Quexil and Sacnab Preclassic levels here assumed to date from approximately 3500 years before the present (1500 B.C.), we recognize an Early Preclassic period that will accommodate the Swasey phase as dated at Cuello, Belize (*3*), but which is not yet known archeologically in the Peten. Some evidence of agricultural disturbance in the third millennium B.C., controversial since first claimed by Tsukada, appears in the full Sacnab and Quexil pollen diagrams, suggesting dates near 3000 B.C. for the lower boundaries of the zone (*59, 60*).

Chemical analyses at 5- to 20-centimeter intervals in sediment cores were for principal cations (by atomic absorption), total carbon and nitrogen (*61*) (by Perkin-Elmer element analyzer), and total phosphorus (after perchloric-acid digestion). For proximate composition of dry sediment, averaged over pollen zones (Figs. 4 and 5), $CaCO_3$ is the CO_3^{2-} equivalent of $Ca^{2+} + Mg^{2+}$; organic carbon (C_{org}) is total carbon minus carbonate carbon; SiO_2 (presumably an aluminum silicate) is the residue after subtraction of C_{org}, $CaCO_3$, and Fe_2O_3. Standard deviations (1σ error) measuring chemical homogeneity of pollen zones are typically 3 to 10 percent for major constituents but average about 35 percent for all variables and zones. Organic carbon, clearly undergoing diagenesis in the top (post-Maya) meter of all cores, is most abundant in Lake Quexil, the least affected lake. Marly sediments, usually containing shells, form the topmost two zones (Late Classic to present) of all cores. Both between zones and between lakes the main compositional differences imply injection of variable amounts of SiO_2, the Maya clay; evidence that $CaCO_3$ and phosphorus are also allochthonous appears when influx rates are calculated.

Influx rates to sediments (Table 3) are subject to errors from known vertical and unknown lateral inhomogeneity of

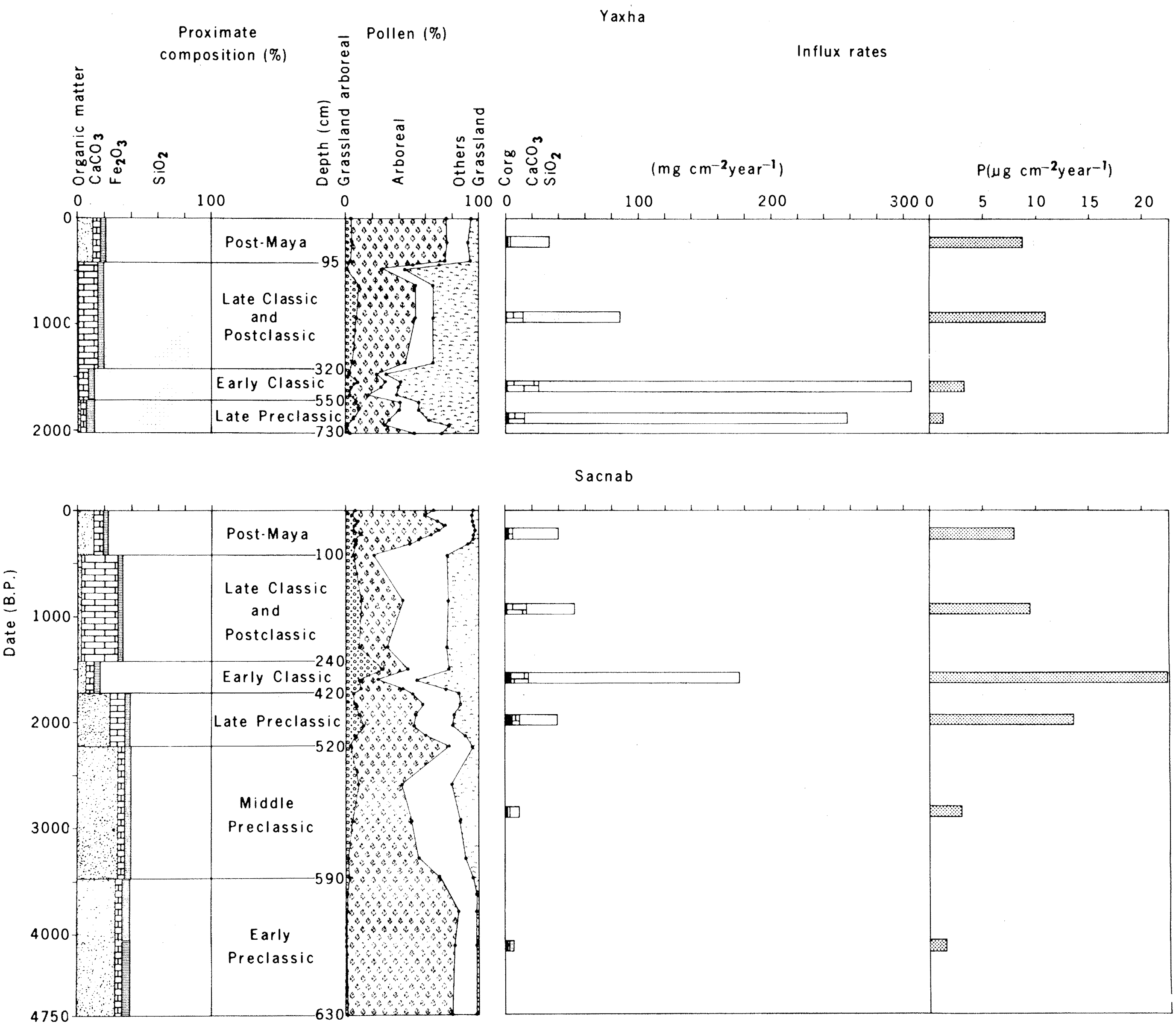

Fig. 4. Composition, relative pollen, and influx rates for dated sediment zones in cores from lakes Yaxha (top) and Sacnab (bottom).

pollen zones, from differential diagenesis, from vertical migration of solutes (believed not to modify total phosphorus in these oxidized sediments), and from dating uncertainties. Collectively, error terms might raise or lower estimates of influx rates by 100 to 200 percent, but such errors cannot explain order-of-magnitude acceleration of influxes with time.

When pre-Maya (Quexil, Fig. 5) or Early Preclassic (Sacnab, Fig. 4) records give early baselines, Early Classic zones of the same lakes exhibit SiO_2 influxes amplified 32 to 35 times; $CaCO_3$ influxes, 20 to 40 times; and phosphorus influxes, 11 to 13 times. The largest SiO_2 influxes (Yaxha, Fig. 4) exceed the Sacnab baseline rate by 55 to 64 times. Late Preclassic and Early Classic Yaxha sediments, evidently mineral soil derived from urban construction, are notably deficient in phosphorus (about 10 ± 9 mg/kg), whereas other zones average 232 ± 76 mg/kg and resemble topsoil (Table 4). Omitting the two low-phosphorus zones, so that there are 15 zones in three lakes, influxes of phosphorus are correlated with those of SiO_2 (r = .914, $P < .001$) and of $CaCO_3$ (r = .743, $P < .001$). Somewhat surprisingly, as marl is usually autochthonous, $CaCO_3$ influxes are also correlated with SiO_2 influxes (r = .753, $P < .001$).

By contrast, influxes of C_{org}, representing autochthonous plant and animal matter, vary less than influxes of the other constituents (by a maximum of seven times); the variances are uncorrelated. Examination of microfossils, which are strikingly rare or visibly degraded in clay zones (*62*), shows that variance of C_{org} influxes results from diagenesis, not from variable photosynthetic production. Sedimentary silicates and carbonates, the fine-grained clastic sediments, are clearly injected as allochthonous deposits. Since Early Classic time, relatively large influxes of phosphorus, for which there is no other adequate source in these closed lakes (*63*), evidently accompanied the clastics. Similar amounts, continuing to enter all three lakes in post-Maya time, must have a similar source.

Soil Phosphorus

Soil samples were taken at 10-cm intervals below forest litter in pits dug to bedrock or, on southern shores, to gravel. We selected 24 samples of 10 cubic decimeters each from six pits (Fig. 3) covering a wide range of topography and soil types. We examined the vertical distributions of total phosphorus and cations in the top two, intermediate, and bottom levels. In contrast to all cations (Ca^{2+} and K^+ are shown in Table 4), phosphorus shows strong and regular gradients diminishing downward. Our phosphorus assays were rechecked and confirmed when cations were measured at the University of Florida (*64*), although our phosphorus analyses (Table 4), carried out by M.B. and M.S.F., averaged 14 ± 15 percent higher; this analytical variance was suppressed, and vertical gradients emphasized, by computing means of the top two and bottom two levels.

Most analyses of soil phosphorus report only phosphate phosphorus, the fraction assumed to be readily available to crop plants and, after overland runoff, plankton. Finding inadequate contributions of phosphorus from runoff and rainwater (*63*), and seeing physical translocation of soils as the main source of sedimentary phosphorus, we measured total phosphorus; the available fraction is not critical if most phosphorus is not transferred to sediments by runoff. Similar concentrations in soil (278 ± 243 mg/kg) and in sediments (208 ± 103 mg/kg, including zones low in phosphorus) are consistent with physical translocation. The large amounts found in topsoil (407 ± 271 mg/kg), which might be found in agricultural soils that have not been recently fertilized, compare favorably with those reported by Eidt (*65*) for anthrosols in the United States and Colombia.

The largest amounts of phosphorus are found throughout the soil profile in pits 1 and 2, at downhill locations near the northern margins of both lakes. Downhill creep of soil is not proved by such data, as phosphorus could be leached from topsoil on ridges and concentrated by runoff. Rapid transport of total phosphorus is contradicted, however, by more homogeneous distributions of K^+

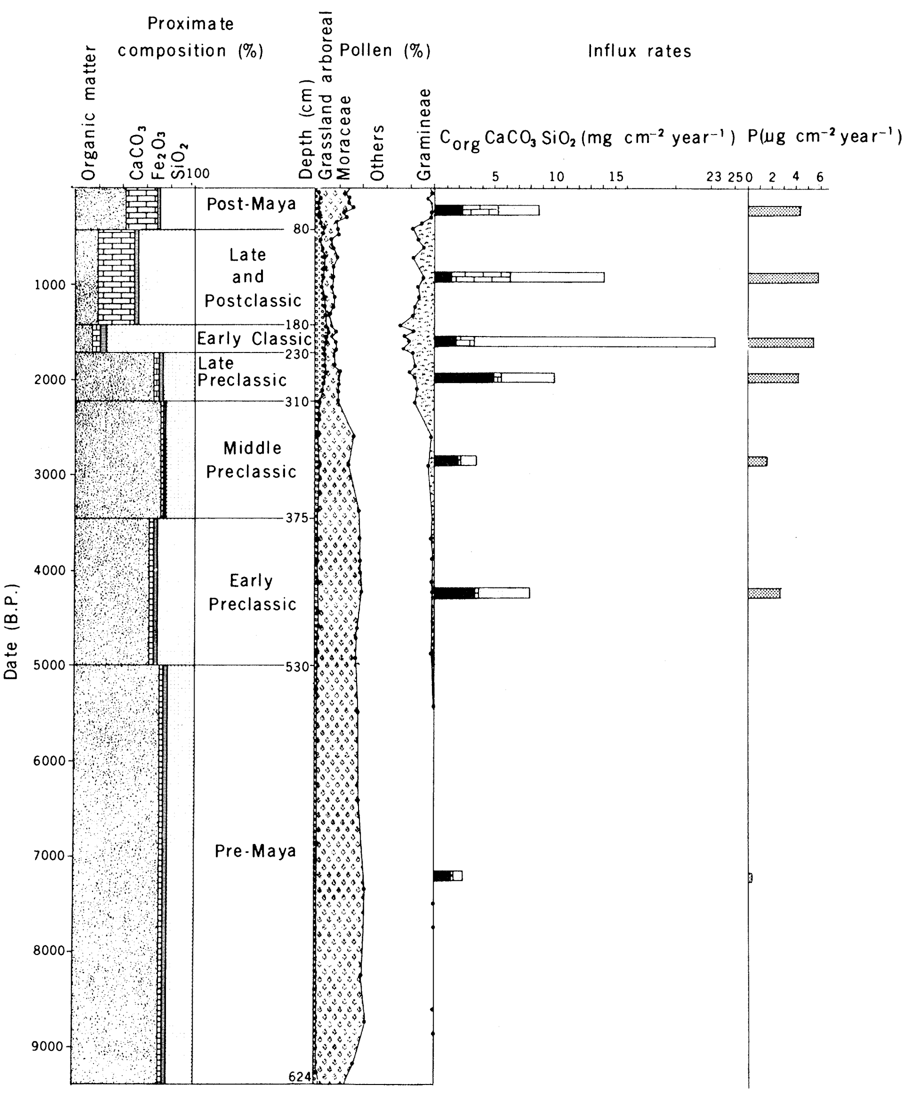

Fig. 5. Proximate chemical composition, relative abundance of principal pollen types, and influx rates of organic carbon, carbonates, silicates, and phosphorus, computed over archeologically dated sediment zones in a core from Lake Quexil.

and other solutes, by maintenance of strong vertical gradients on ridges, and by continued large post-Maya influxes to the lakes. We infer that phosphorus is slowly moving from basins to lakes at rates more consonant with bulk transfer than with leaching.

Phosphorus Loading Rates

Most temperate-zone lakes receive 100 to 1000 mg/m^2-year (10 to 100 μg/cm^2-year) of total phosphorus; above 500 mg/m^2-year the principal sources are human sewage and agricultural effluents (*66*). Lower loading rates (30 to 130 mg/m^2-year) are reported from unproductive and relatively undisturbed lakes in Nova Scotia (*67*) and central Florida (*68*). In agricultural regions (and near Florida phosphate mines) the atmospheric load (20 to 70 mg/m^2-year) can be the largest influx to small lakes, but rainfall at Hubbard Brook, New Hampshire (phosphorus content, 4.2 mg/m^2-year), contributes much less phosphorus (*69*), as does rainfall in the Peten (*63*). In Algonquin Park, Ontario, of the annual phosphorus received by Kearney Lake (221 mg/m^2) rainfall supplies 16 percent, and one seasonal campground supplies 22 percent (*70*).

In comparison, influxes of total phosphorus to lakes Yaxha and Sacnab [range, 80.5 to 110.2 mg/m^2-year (Table 3) since Late Classic time] may seem surprisingly high. They approach or exceed the "tolerable" level (100 mg/m^2-year) (*71*) for lakes of <10 m mean depth; the Early Classic influx to Lake Sacnab, 223.8 mg/m^2-year, would be "dangerous" in Europe and North America. These figures may be misleadingly high, however, if relatively little of the total phosphorus was biologically available (*66*). Because sedimentary carbon has been lost, in part by molar action of clastic sediments (*62*), eutrophication cannot be demonstrated by our data and may have been impeded by siltation.

Phosphorus budgets, as modeled in many lakes, successfully predict phosphorus concentrations and plankton blooms as a function of human effluents (*66, 71, 72*). Where sewage outfalls provide point sources, measured outputs per capita range above 0.55 kg/year, a minimal figure expected if bodily ingestion and excretion of phosphorus are in steady state (*73*). Disposal of manure, garbage, and detergents raises observed outputs to > 1.5 kg per capita per year. Delivery of excess phosphorus from farmlands and septic-tank fields is slowed (on an engineer's time scale) by retention of phosphorus in soil. For a typical temperate-zone mix of urban and rural landscapes the Dillon-Rigler (modified Vollenweider) model (*74*) assumes 0.8 kg/year as the net per capita delivery rate (a function of societal output but not to be confused with it). The campground on Kearney Lake, occupied in summer by about 200 campers (40.6 person-years per year (*70*), delivers 0.48 kg of phosphorus per capita per year; agreement with the physiological output is doubtless coincidental, but it implies rapid delivery of excess phosphorus from Precambrian basins.

These data suggest that Mayan outputs of excreted phosphorus should have been about 0.5 kg per capita per year. Other societal outputs—from fertilizers (such as dead fish), food wastes, and mortuary corruption (*75*), including that of sacrificial victims—should raise the figure, though probably not to the 2 kg per capita per year observed where detergents are used. After centuries of soil creep, rough equilibration can be expected between societal production and delivery of phosphorus to the lakes. Forest clearance constitutes another societal output, which should appear as a Preclassic flush of phosphorus, enhancing the per capita delivery rate. Conversely, apparent delivery rates will be much smaller than 0.5 kg per capita per year (i) if urban construction delivered large amounts of clastic sediments unusually poor in phosphorus or (ii) if producing

Table 3. Influxes to lake sediments, given as amount per square centimeter per year.

Zone	Thickness (cm)	Interval (year)	Dry weight (mg)	C_{org} (mg)	$CaCO_3$ (mg)	SiO_2 (mg)	P_{total} (μg)
			Yaxha				
Post-Maya	95	420	37.55	1.95	1.93	29.50	8.58
Late and Postclassic	225	1000	90.90	0.35	13.15	72.99	11.02
Early Classic	230	300	322.00	0.89	23.90	282.06	3.25
Late Preclassic	185	300	275.03	2.54	11.59	244.09	1.29
			Sacnab				
Post-Maya	100	420	44.76	2.34	3.07	34.73	8.05
Late and Postclassic	140	1000	54.88	0.67	14.85	36.59	9.57
Early Classic	180	300	190.20	4.19	12.99	159.27	22.38
Late Preclassic	100	500	47.20	5.17	4.74	29.04	13.65
Middle Preclassic	70	1250	13.55	1.85	0.69	8.16	3.14
Early Preclassic	40	1280	7.19	0.93	0.32	4.43	1.70
			Quexil				
Post-Maya	80	420	15.71	2.21	3.05	3.53	4.39
Late and Postclassic	100	1000	19.00	1.33	4.96	7.81	5.87
Early Classic	50	300	29.00	1.66	1.64	20.00	5.76
Late Preclassic	80	500	18.56	4.78	0.74	4.41	4.22
Middle Preclassic	65	1250	6.66	1.78	0.20	1.46	1.71
Early Preclassic	155	1530	15.05	3.26	0.33	4.19	2.67
Pre-Maya	94	4400	2.80	1.25	0.15	0.91	0.66

Table 4. Concentrations of Ca^{2+} (milligrams per gram) and of K^+ and total phosphorus (milligrams per kilogram) in soil profiles.

Pit number	Location	Depth (cm)	Ca^{2+} (mg/g)	K^+ (mg/kg)	P_{total} (mg/kg)
		Yaxha basin			
3	Northern	0 to 20	258	965	385
	ridge	70 to 140	307	475	135
1	Near northern	0 to 20	250	880	689
	shore	30 to 60	293	690	360
6	Southern	0 to 20	323	520	141
	shore	50 to 90	338	640	44
		Sacnab basin			
4	Northern	0 to 20	158	850	365
	ridge	20 to 120	98	360	98
2	Near northern	0 to 20	246	775	760
	shore	40 to 80	315	720	218
5	Southern	0 to 30	333	575	105
	shore	70 to 130	357	385	34
		Means ± 1 standard deviation			
Whole profile			273 ± 76	653 ± 201	278 ± 243
Top two levels			261 ± 63	761 ± 177	407 ± 271
Bottom two levels			285 ± 94	545 ± 158	148 ± 123

populations or effective riparian areas are overestimated.

Seeking explanation of remarkably large influxes of phosphorus in terms of large amounts of disturbed soil, we first (76) projected intensities of disturbance on transects to the entire Yaxha-Sacnab topographic basin, 130 km^2 (47). Being conservative in respect to rates of phosphorus transfer, the assumption posits huge Late Classic populations of 22×10^3 to 33×10^3 people, few of whom can have contributed much phosphorus to the lakes. Estimates of apparent output—30 to 100 g per capita per year at maximum densities—are therefore unreasonably low.

When riparian populations are assumed to have occupied subbasins delimited by the 200-m contour (Table 1, column 4), calculated per-capita outputs (77) are as in Table 2. Maximum populations (2130 on Lake Yaxha, 3650 on Lake Sacnab) are not unreasonable (except in relative proportion), and maximum deliveries of phosphorus, from 0.61 to 1.46 kg per capita per year, are of the right order. Hypothetical post-Maya outputs (not entered in Table 2) are equivalent to persistence of 78 to 84 percent of Late and Postclassic mean populations. Late Preclassic and Early Classic zones high in SiO_2 in Lake Yaxha yield anomalously low per-capita delivery rates, as expected. Whether because of this anomaly or because the section is too short, any effect of deforestation on Lake Yaxha is obscured, but the anticipated flush of phosphorus appears in the Late Preclassic zone of Lake Sacnab. Omitting the low-phosphorus urban-silt zones in Lake Yaxha, the harmonic mean of five estimates of Mayan phosphorus output is 0.49 kg per capita per year.

As the 200-m contour probably overestimates the land area, and therefore the effective population of Lake Sacnab, we calculated apparent delivery rates from 2-km basins (Table 1, column 5). Reversing the relative sizes of riparian populations reverses the bias on per capita delivery rates, reducing Yaxha rates by a factor of approximately one-third and enhancing Sacnab rates by about three-quarters, but makes no other important changes; the mean of five estimates becomes 0.57 kg of phosphorus per capita per year. Either assumption selects basins from which adequate amounts of phosphorus can reach the lakes. Similarity of per-capita deliveries over Mayan time supports the inference that excess phosphorus was delivered in rough proportion to its production. Because of high variance, however, statistical significance cannot be claimed for the Late Preclassic maximum in Lake Sacnab.

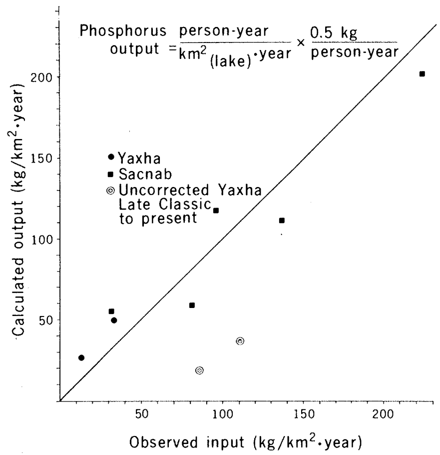

Fig. 6. Test of model (Eq. 1) relating observed deliveries of phosphorus to sediment zones of lakes Yaxha and Sacnab to calculated outputs, at 0.5 kg of phosphorus per capita per year, of estimated mean riparian populations from Middle Preclassic through Postclassic and post-Maya time (77). Hypothetical post-Maya outputs assume persistence of half of the mean Late Classic plus Postclassic populations.

The nutrient-loading model that fits these data (Fig. 6) is simple:

$$\dot{D} = R\ O_M \bar{X}_r \quad (1)$$

where $\dot{D}$ is the delivery rate of phosphorus in kilograms per square kilometer per year, $\bar{X}_r$ is mean effective (riparian) population in persons per square kilometer of lake area, O_M is Mayan output in kilograms of phosphorus per capita per year, and R is the fraction of output ultimately delivered after retention by soil. The retention constant R, here taken as reaching unity after slow equilibration with output over long times, should also approach 1.0 if delivery of excess phosphorus is completed on a shorter time scale, as from a population served by sewers.

As computed for Fig. 6, the model assumes the 200-m basin, $R = 1$, $O_M = 0.5$ kg per capita per year, and speculatively allows post-Maya delivery rates to remember populations half the size of Late + Postclassic means. No ad hoc assumption is made to correct for urban siltation in Lake Yaxha. Of the two most deviant points in Fig. 6, one is hypothetical post-Maya value, and both reflect the upward bias on Yaxha delivery rates imposed by underestimates of the relative size of Yaxha's basin.

A more general form of the model would substitute societal output, O_s, for O_M:

$$\dot{D} = R\ O_s \bar{X}_r \quad (2)$$

Societal output of phosphorus can then be partitioned into components:

$$O_s = O_a + O_b + \ldots O_j \quad (3)$$

where O_a is the physiological output and $O_b \ldots O_j$ are increments from food waste, fertilizers, detergents, and so forth.

We have tried without success to evaluate $O_b \ldots O_j$ for the Yaxha-Sacnab population. Virtual transfer of phosphorus (78) from disturbed soil (Table 2) are linearly related to nonurban populations (Fig. 2), and differences between lakes in virtual transfers are as sensitive as per capita outputs to relative land areas assumed to be riparian. As urban silt is nonphosphatic, no measure of urban phosphorus output is reliably independent of SiO_2 influx, and the problem is intractable. If chronological resolution were finer, or if population data were available from several lakes, analyses of variance might separate physiological from other societal outputs. Where $N = 5$ phosphatic zones, four of which are in a single less-urbanized lake; statistical methods cannot embellish the demonstration that $O_s \cong O_a \cong 0.5$ kg of phosphorus per capita per year. Release of excess phosphorus by deforestation or by human sacrifice could easily double or triple per capita outputs, but such surmises cannot be confirmed without additional data.

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