



ACADEMIC
PRESS

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Journal of Anthropological Archaeology 22 (2003) 126–161

JOURNAL OF
Anthropological
Archaeology

www.elsevier.com/locate/jaa

The intensification of pre-industrial cereal agriculture in the tropics: Boserup, cultivation lengthening, and the Classic Maya

Kevin J. Johnston*

Department of Anthropology, Ohio State University, 244 Lord Hall, 124 W. 17th Avenue, Columbus, OH 43210-1364, USA

Received 10 September 2002; revised 5 December 2002

Abstract

Through a review of recent research in tropical ecology, soils science, and agronomy, this paper develops a model of tropical agricultural intensification through cultivation lengthening that applies to non-industrial cereal production in moist-to-wet tropical lowlands under conditions of high population density. Contrary to the predictions of many archaeological models, in tropical agricultural societies lacking plows, draft animals, or chemical fertilizers, or in which irrigation or intensive wetland agriculture are not practiced, progressive reduction and eventual elimination of the fallow period is not the only ecologically feasible means of intensifying agricultural production. More productive and sustainable under certain circumstances is intensification through cultivation lengthening, wherein farmers increase per hectare crop outputs through intensive weeding and mulching. To demonstrate the model's analytical utility I apply it to the case of population growth and agricultural intensification in the Classic-period southern Maya lowlands of Mesoamerica. I propose that prior to the ninth-century Maya "collapse," some but not all high-density southern lowland populations included cultivation lengthening in their repertoire of intensification strategies. Adoption of the practice helps explain how high-density populations sustained themselves agriculturally for decades after surpassing the productive limitations of alternative intensification strategies. My model of cultivation lengthening is an elaboration of a largely overlooked proposal made several decades ago by Ester Boserup.

© 2003 Elsevier Science (USA). All rights reserved.

Keywords: Intensification; Tropical agriculture; Population growth; Cereal cultivation; Ester Boserup; Maya archaeology; Mesoamerica

Introduction

In archaeological discussions of the relationship between population and agricultural dynamics, few contributions have generated more interest or controversy than Boserup's (1965, 1981, 1990) proposal that in pre-industrial societies, as farmers intensify agricultural production, cultivation systems pass through a unilineal and universal sequence of evolutionary stages, each of

which is distinguished by a specific range of cropping frequencies. Boserup predicts that in non-industrial settings, the evolution of agricultural systems is propelled by intensification, which farmers achieve primarily by increasing the frequency with which they crop their fields. Through fallow shortening agricultural systems are propelled through "the main stages of the actual evolution of primitive agriculture" (Boserup, 1965, pp. 15–18), wherein, prompted by food demand increases precipitated by population growth, farmers shift from long fallow to shorter fallow and eventually to no-fallow systems of cultivation.

* Fax: 1-614-292-4155.

E-mail address: johnston.213@osu.edu.

The shortcomings of Boserup's model of the evolution of pre-industrial agriculture are well known. As archaeologists and other social scientists have demonstrated, pre-industrial agricultural intensification often follows not a single, unilineal, or progressive course, as Boserup predicts, but multiple courses observable as heterogeneous strategies that farmers pursue simultaneously but in different ways throughout society (Kirch, 1994; Leach, 1999; Morrison, 1994, 1996). Contrary to Boserup's predictions, increasing cropping frequency is not the only available means of intensifying non-industrial agricultural production, and even where it is, farmers often increase cropping frequency through means other than fallow reduction (Kirch, 1994; Leach, 1999; Morrison, 1994–1996; Stone, 1996). Similarly, population growth and land shortages are not in all cases the primary inducements to intensification (Brookfield, 1972; Kirch, 1994, pp. 16, 306–312; Morrison, 1994; Stone and Downum, 1999, p. 115), and environmental variables do affect intensification (Kirch, 1994, pp. 16, 307; Stone and Downum, 1999, p. 115). Also flawed is Boserup's contention that particular technologies are adopted during specific "stages" of agricultural evolution. Contrary to her predictions, for example, those practicing the most labor-intensive production strategies do not always employ the most complex technologies (Bray, 1986; Morrison, 1994, pp. 135–136). Nonetheless, Boserup's model is not without merit (cf., Athens, 1999; Spriggs, 1999; Stone, 1996; Stone and Downum, 1999; Wilk, 1995). As Stone and Downum (1999) astutely observe, Boserupian intensification occurs only under specific agroecological conditions, and outside these conditions her model does not hold.

This paper contributes to the ongoing the anthropological critique of Boserup's work by examining a component of her model that archaeologists and other social scientists have largely overlooked: her proposal that under certain conditions, pre-industrial farmers can intensify production through intensive bush fallow cultivation. Under intensive bush fallow cultivation, farmers intensify production by increasing the number of years during which individual plots are cultivated on an annual basis before fallowing—a practice hereafter described as "cultivation lengthening." Within the context of Boserup's evolutionary model, cultivation lengthening is distinctive because it inverts (albeit temporarily) what is alleged to be the main evolutionary thrust of pre-industrial intensification: farmers' attempts to increase cropping frequency by progressively shortening fallow periods.

Although archaeologists have documented many pre-industrial intensification practices and courses not identified by Boserup (e.g., Kirch, 1994; Morrison, 1994, 1996), few have critically examined the practice of cultivation lengthening. This paper asks, is the intensification of bush fallow cultivation through cultivation

lengthening ecologically feasible in pre-industrial agricultural societies? I conclude that, under certain ecological conditions, it is. In reaching this conclusion, I do not endorse Boserup's stage-based model of agricultural evolution, her proposal that environmental variables have little effect on intensification, or her linkage of particular technologies to specific evolutionary "stages."

From an archaeological perspective, the fact that intensive bush fallow cultivation is ecologically feasible under certain conditions is significant because use of the practice in antiquity could account for processes that have long resisted explanation. Among these is the relationship in southern lowland Classic Maya (ca. AD 550–800) society between population growth, agricultural intensification, and profound cultural change. On the basis of population estimates derived from settlement data and estimates of the productive capacity of the agricultural technologies known to have been employed by the Maya, several archaeologists have concluded that during the seventh and eighth centuries AD, some high-density southern lowland Maya populations must have exceeded the productive capacity of their agricultural systems. If current estimates of Maya maximum population densities are reasonable—an assumption that some Mayanists (Ford, 1991; Webster, 2002, pp. 174, 264) reject—then archaeologists must ask, how did high-density Maya populations support themselves agriculturally? One intensification strategy not previously considered by Mesoamericanists is intensive bush fallow cultivation. That intensive bush fallow cultivation could have been an intensification option for the Classic Maya is suggested by recent research in the biological and agricultural sciences, which indicates that in certain tropical environments, including the southern Maya lowlands of Mesoamerica, intensive bush fallow cultivation can be highly productive and sustainable.

Referring to recent research in tropical ecology, soils science, and agronomy, this paper presents a model of the ecological dynamics that can render intensive bush fallow cultivation a productive and sustainable practice in certain tropical environments. The model applies only to pre- or non-industrial tropical cereal cultivation in some moist-to-wet tropical environments. It does not apply to tropical root crop or rice paddy cultivation. To demonstrate the model's potential analytical utility in archaeology, I apply it to the case of population growth and agricultural intensification in the Classic-period southern Maya lowlands of Mesoamerica. Before examining the model and its archaeological implications, I review Boserup's description of: (a) intensive bush fallow cultivation and (b) the conventional model of tropical ecology that it challenges. That conventional model of tropical ecology underlies much current archaeological thinking about the relationship in Classic Maya society between population growth, agricultural intensification,

anthropogenic change, and the ninth-century collapse of southern lowland complex society. Next I review what archaeologists currently know about: (a) Maya population size, density, and growth rate trends, (b) Maya agricultural (including intensification) strategies, (c) the anthropogenic effects of intensification, and (d) the ecological foundations of the southern lowland Maya collapse. After presenting my model of tropical swidden intensification of cereal crops through intensive bush fallow cultivation, I conclude by examining its implications for Maya archaeology and for archaeological investigations of pre-industrial agricultural intensification in the tropics.

Tropical agricultural intensification: Boserupian and ecological models

Agricultural intensification through fallow reduction

Among the components of Boserup's model most widely cited and criticized by archaeologists is her five-stage model of the evolution of "primitive agriculture" (i.e., pre-industrial swidden cultivation and its outgrowths) outlined in *The Conditions of Agricultural Growth* (1965) and later volumes (1981, 1990). According to Boserup, pre-industrial peoples intensify agricultural production primarily by shortening the fallow period. As illustrated in Table 1, each evolutionary stage is characterized by a specific land use intensity [defined by fallow period length (Boserup, 1965, pp. 15–16; Hunt, 2000, p. 261)], plant succession communities, cropping technologies, and soil fertilization practices.

The weakness and limitations of Boserup's model are well documented (Hunt, 2000; Kirch, 1994; Leach, 1999; Morrison, 1994, 1998; Stone, 1996; Stone and Downum, 1999). Not widely commented upon is the fact that her evolutionary scheme encompasses two (not one) alternative developmental trajectories. The second developmental trajectory is distinguished from the first by its third evolutionary stage, composed of a suite of intensification practices collectively called "intensive bush fallow" cultivation. From an archaeological perspective, intensive bush fallow cultivation is of interest because it constitutes a distinct, largely unexplored intensification course whose ecological viability has yet to be established. If intensive bush fallow cultivation is viable, archaeologists should add it to the growing list of pre-industrial intensification courses now documented in the literature (e.g., Kirch, 1994; Morrison, 1994, 1998).

As illustrated in Table 1, both of the two trajectories begin with forest fallow cultivation, which is followed by extensive bush fallow cultivation. Under forest fallow cultivation, farmers cultivate plots for one to two years and fallow them for 20–25 years, during which time

fields reforest with "true forest" vegetation (Boserup, 1965, pp. 15, 25). Farmers introduce fertilizer to fields in the form of the ash produced by the burning of felled forest vegetation. Weeding is not necessary because forest fallow displaces weeds (Boserup, 1965, pp. 24–25). Axes and digging sticks are the principal agricultural tools.

When, because of population growth, forest fallow farmers are obliged to intensify production, they do so by shortening the fallow period to 6–10 years, whereupon they are said to practice bush fallow cultivation. Boserup envisions two types of bush fallow cultivation, one extensive, the other intensive (Boserup, 1965, pp. 24–26, 53; 1981, p. 44). Under extensive bush fallow cultivation, fallow vegetation consists of bushes and some small trees, which when burned produce amounts of ash too small to maintain the soil nutrient levels necessary for agriculture. To enhance soil fertility, farmers bring "burnt and unburnt leaves or other vegetable materials and turf... to the cultivated lands from the surrounding bush and [mix them] with the topsoil by means of hoeing" (Boserup, 1965, p. 25). Cultivators rarely weed because grass growth in extensive bush fallow plots usually is moderate (Boserup, 1965, p. 25).

Beyond the extensive bush fallow cultivation stage, agricultural intensification can follow either of two developmental trajectories. In the first trajectory, extensive bush fallow is followed by short fallow cultivation, characterized by fallow periods and cultivation periods of only one to two years. Many describe this practice as grass fallow cultivation (e.g., Sanders, 1973) because during its fallow period, primarily wild grasses colonize plots (Boserup, 1965, p. 15). At the start of each growing season short fallow cultivators burn their plots, but because fire does not destroy the roots (and thus the short-term regrowth potential) of the grasses that infest plots, farmers must plow fields before cultivating them (Boserup, 1965, pp. 24–25). Boserup contends that only farmers with access to plows can intensify production through short fallow cultivation (1965, pp. 25, 32). Pre-industrial plowing presupposes the existence of draught animals, whose manure farmers spread on plots to fertilize them (Boserup, 1965, p. 25).

In both the first and the second developmental trajectories, the fallow period is all but eliminated during the final two stages of intensification, known as annual cropping and multicropping, respectively. Under annual cropping, farmers cultivate fields once a year and allow only a few months per annum for fallowing. Under multicropping, each plot bears two or more successive crops each year, and there is little time for fallowing between harvest and the planting of the next crop (Boserup, 1965, p. 16). During both stages, farmers boost soil nutrient levels through "green manuring, marling, composts, including household waste, silt from canals, etc." (Boserup, 1965, p. 25).

Table 1
Ester Boserup's two trajectories of non-industrial agricultural intensification (after Boserup, 1965; Redman, 1999)

Agricultural stage	Cultivation period	Fallow period	Technology	Weeding	Fertilization techniques	Fallow vegetation
<i>Boserup's first intensification trajectory</i>						
Forest fallow	1–2 yr	15–25 yr	Dibble stick	“Unnecessary”	Ash from burn	Forest
Extensive bush fallow	1–2 yr	6–10 yr	Dibble stick	“Rarely used”	Green manuring, mulching	Bush
Short fallow	1–2 yr	1–2 yr	Plow	“Rarely used”	Animal manure, human wastes	Grass
Annual cropping	1 crop/yr	Few months	Plow or irrigation, possibly terracing	“Indispensable”	Green manuring, marling, composts	Grass
Multicropping	≥2 crops/yr	No fallow	Irrigation, possibly terracing	“Indispensable”	Green manuring, marling, composts	None
<i>Boserup's second intensification trajectory</i>						
Forest fallow	1–2 yr	15–25 yr	Dibble stick	“Unnecessary”	Ash from burn	Forest
Extensive bush fallow	1–2 yr	6–10 yr	Dibble stick	“Rarely used”	Green manuring, mulching	Bush
Intensive bush fallow	6–8 yr	6–8 yr	Hoe	“Indispensable” and intensive	Highly intensive mulching	Bush
Annual cropping	1 crop/yr	Few months	Plow or irrigation, possibly terracing	“Indispensable”	Green manuring, marling, composts	Grass
Multicropping	≥2 crops/yr	No fallow	Irrigation, possibly terracing	“Indispensable”	Green manuring, marling, composts	None

Source. Boserup (1965) and Redman (1999).

Cultivation lengthening: Intensification through intensive bush fallow cultivation

Under Boserup's second evolutionary trajectory, the extensive bush fallow cultivation stage is followed not by short fallow cultivation but by intensive bush fallow cultivation. Moreover, during the transition to intensive bush fallow cultivation, farmers intensify production not by further shortening the fallow period, as short fallow cultivators do, but by lengthening the cultivation period, during which plots are successively cultivated on an annual basis—the practice of cultivation lengthening. Under intensive bush fallow cultivation, farmers increase the length of the cultivation period from one to two years (diagnostic of extensive bush fallow cultivation) to six to eight years (Boserup, 1965, pp. 15, 25). Because bush fallow intensification, or “the lengthening of the period of successive cultivation on a given plot” (Boserup, 1965, p. 30), entails an increase in cropping frequency, it constitutes a form of intensification. Intensive bush fallow cultivation changes crop-to-fallow ratios to the advantage of the farmer: under extensive bush fallow cultivation crop-to-fallow ratios range from 1:3 to 1:4; under intensive bush fallow cultivation they increase to 1:1.5 or 1:1. Over time, intensive bush fallow cultivation doubles, triples, or even quadruples cropping frequency relative to extensive bush fallow cultivation.

According to Boserup, short fallow cultivation and intensive bush fallow cultivation are mutually exclusive evolutionary alternatives (Boserup, 1965, p. 25; 1981, p. 41). That is, extensive bush fallow cultivators can intensify production by adopting either short fallow cultivation or extensive bush fallow cultivation, but the practices never follow one another. Why do some extensive bush fallow farmers intensify production through intensive bush fallow cultivation rather than short fallow cultivation? Boserup provides the following explanation:

The need of a plough for short-fallow cultivation is so compelling that cultivators usually avoid the stage of short fallow if they are unable to use ploughs, owing to a lack of animals or for some other reason. Such cultivators prolong the period of cultivation under bush fallow up to eight years or more instead of shortening the period of fallow. By re-cultivating the land year after year they avoid an excessive spreading of the wild grasses, and by keeping a relatively long fallow period when cultivation periods are over, they give the bush a chance to cover the land and thus prevent its becoming too grassy. The result is the type of *intensive bush fallow* which can be observed for instance in many parts of Africa, where *cultivation periods of up to eight years alternate with fallow periods of similar length* (1965, p. 25, emphases added).

To maintain soil fertility, intensive bush fallow cultivators add to fields “burnt and unburnt leaves [and]

other vegetable materials and turf brought to the cultivated lands from the surrounding bush and mixed with the topsoil by means of hoeing” (Boserup, 1965, p. 25). A combination of “very labour-intensive methods—for land preparation, manuring, and weeding—must be employed if crop yields are to be kept unchanged (maintained or increased) despite the longer periods of uninterrupted cultivation of the land” (Boserup, 1965, p. 31). Weeding becomes an “indispensable” (Boserup, 1965, pp. 25–26), highly labor-intensive activity, which in some cases keeps farming families busy “from sunrise to sunset” during the cultivation season (Boserup, 1965, p. 48).¹

As described by Boserup, the principal attributes of intensive bush fallow cultivation are as follows:

1. Under intensive bush fallow cultivation, farmers fallow fields for 6–10 years (or more) because fallowing for shorter periods can cause fields to convert to grasslands.
2. Extensive and intensive forms of bush fallow cultivation are distinguished on the grounds of the length of the cultivation period: one to two years under the former, minimally six to eight years under the latter. Crop-to-fallow ratios shift from 1:3, 1:4, or even 1:10 under extensive bush fallow to 1:1.5 or 1:1 under intensive bush fallow.
3. Intensive bush fallow cultivators maintain soil fertility and control weed growth through weeding and mulching—both highly labor-intensive activities.²
4. Extensive bush fallow cultivators adopt intensive bush fallow cultivation only when progression to short fallow cultivation, the alternative intensification course, is desired but cannot be achieved because plowing is not an option.

After the intensive bush-fallow cultivation stage, Boserup's two developmental trajectories converge. That is, to intensify production, intensive bush fallow cultivators adopt either annual cropping or multicropping (Boserup, 1965, pp. 36, 41–42).

Although Boserup refers to the practice repeatedly (1965, pp. 25, 30, 31, 36, 41, 42, 48, 53), her suggestion that pre-industrial farmers can intensify production by lengthening the cultivation period rather than shortening

¹ This paper does not evaluate Boserup's proposal that farmers will intensify production through cultivation lengthening only when plowing is not possible. I examine the ecological viability of cultivation lengthening rather than the technological context of its development.

² Boserup observes: “In some cases of intensive bush fallow the peak may be so busy a period that the family, even when working hard all day, finds it difficult to manage the area needed for subsistence. This is especially so in places where the land has become infested with grasses which make hoeing difficult or require frequent weeding in the rainy season. Examples of this type of very arduous peak-time activity are found in parts of Sudan and Ethiopia...” (1965, p. 48).

the fallow period (at a particular stage of agricultural development) has received little critical attention. Why has her proposal been so widely overlooked? Two explanations come to mind. First, Boserup's discussion of cultivation lengthening through intensive bush fallow cultivation is not clearly articulated, and it is scattered through examinations of other topics. In other words, it is easily overlooked. Second, Boserup cites tropical [e.g., African (1965, pp. 25, 48)] agricultural data to support her model of cultivation lengthening. But judging from the conventional model of tropical ecology that dominated the biological, agricultural, and social sciences during the most productive years of Boserup's scholarship, in pre-industrial agricultural systems, cultivation lengthening is not an ecologically feasible intensification practice.³ Thus, scholars in the social sciences may have been inclined to dismiss, ignore, or misunderstand Boserup's proposal because it was inconsistent with the conventional model of tropical ecology, which many of them embraced. Among these scholars were many Mayanists, whose reconstructions of: (a) the development of ancient Maya agriculture and (b) the ecological foundations of the Classic-period collapse of southern lowland Maya complex society were (and remain) deeply informed by the conventional model of tropical ecology. It is now known that key components of that conventional model are in error. Before examining its implications for research in Maya archaeology, I briefly review the conventional model of tropical ecology.

The traditional model of the ecological dynamics of tropical agriculture

Through the 1970s and 80s, the conventional model of tropical ecology dominated the thinking of many ecologists (e.g., Nye and Greenland, 1960; Richards, 1952), geographers (e.g., Gourou, 1953), demographers (e.g., Weiner, 1972), and development specialists (Food and Agriculture Organization, 1958; Watters, 1971) about tropical agriculture. Richter and Babbar (1991) and Sanchez and Logan (1992) review the historical development of one of the principal tenets of the conventional model, that tropical soils are universally infertile, which led many to conclude that under cultivation, tropical soils cannot retain key nutrients needed for crop production.

Proponents of the conventional model of tropical ecology agree with proponents of a newer, more recently developed model (described below) on several key points. In moist tropical rainforests, surface temperature and humidity are high because of the hot, wet climate, and in these ecosystems nutrient cycling is rapid and

nearly closed. Fallen plant matter decays quickly and its carbon and mineral content is absorbed from the soil with extreme efficiency by the roots of forest plants. Under forested conditions, many of the nutrients needed for agriculture (e.g., nitrogen, calcium, potassium, and magnesium) reside not in the soil but in the vegetation that the soil supports, and some but not all tropical soils are nutrient poor.⁴ To cultivate in tropical rainforests, farmers free the nutrients stored in forest vegetation and move them into the soils. This they accomplish through slashing and burning, whereby forest trees and shrubs are felled, allowed to dry, and burned, which transforms the vegetative biomass into a nutrient-rich layer of ash that carpets and fertilizes the soil. The practice also allows sunlight to reach crops and eliminates tree competition for soil nutrients (Jordan, 1985).

From this information proponents of the conventional model propose the following (Kricher, 1989; Nye and Greenland, 1960). When farmers cut down the forest for agriculture, they remove a key element of the nutrient cycling system and thus open the system to nutrient loss. Most nutrients in tropical soils reside in the uppermost soil levels, where, under forested conditions, the roots of trees and shrubs are most dense. When farmers remove the forest for agriculture and partially destroy the surface mat of roots through burning, nutrients leach out of the upper soil levels. Nutrient leaching takes two major forms: percolation down into the subsoil, where nutrients no longer are available to shallow-rooted plants (including most cultigens), and loss through surface runoff and topsoil erosion during seasonal rainfall. Deforestation also removes the source of nutrients: the forest, whose dropped leaves, branches, and trunks provide the decayed vegetative matter whose nutrient contents the system recycles. The volatilization of carbon, nitrogen, and sulfur, especially during the burn, is another important flux through which nutrients are lost.

When forest biomass, the source of nutrient production, is removed for agriculture and the nutrient content of soils is depleted through leaching and absorption by crops, the nutrient stocks of fields stored in soils slowly and inexorably declines. After the second year of cultivation, soil nutrient stocks may be so depauperate that continued cultivation no longer is possible. When crop yields decline precipitously farmers are obliged (or find it economic) to abandon fields to lie fallow for a number of years. Swidden farming in the Maya lowlands is a case in point. Depending on local soil conditions, land tenure arrangements, and food

³ Boserup (1965, pp. 18–19) explicitly rejected key proposals of that conventional model, including the idea that tropical soils are inherently nutrient-poor.

⁴ Only in a few very poor oxisols and spodosols are there insufficient nutrients for agriculture, and even in these soils there usually is more nitrogen (incorporated in the soil organic matter) and phosphorus (held by iron and aluminum in Oxisols) than in the forest (Jordan, 1985).

demands, modern Maya swidden farmers fallow their fields for between 4 and 10 years (with an average of about six) for every year of cultivation (Atran, 1993, p. 681; Cowgill, 1962, p. 76; Ewell and Merrill-Sands, 1987, p. 109; Nations and Nigh, 1980, p. 8; Sanders, 1973, p. 347). Thus in modern Maya farming the crop-to-fallow ratio typically ranges from 1:4 to 1:10. Farmers explain that after a few years of cultivation they are obliged to fallow fields because grasses rapidly invade fields and, more significantly, crop yields sharply decline.

Proponents of the conventional model of tropical ecology assume that post-second-year crop yield declines are an appropriate proxy for soil nutrient stocks, and they attribute these yield declines to soil nutrient declines caused by leaching. Once soil nutrient stocks decline below minimum levels necessary for swidden agriculture, farmers must fallow their fields. Fallowing allows fields to reforest, and reforestation is the process whereby the nutrient stocks in vegetation needed for agriculture are replenished. Any process that slows down or interferes with the reforestation process—e.g., aggressive grass invasion—compromises the field's potential future productivity.

Advocates of the conventional ecology model have long wondered what is the primary cause of crop yield declines after the second year of cultivation: soil nutrient declines or weed invasions? Nye and Greenland (1960, p. 76) summarize the problem as follows: “it is frequently difficult to decide whether falling yields are due to weeds or to declining (soil) fertility. Poor crops tend to be weedy; are weeds the cause or the effect?” Do weeds invade fields because the nutrient content of their soils is depleted, or is weed invasion a cause of soil nutrient depletion and thus of crop yield declines? Some of the most influential research on this question has been carried out in the Maya lowlands by advocates of the conventional model of the ecological dynamics of tropical swidden agriculture (e.g., Cook, 1909, 1921; Watters, 1971), who conclude that the primary cause of post-second-year swidden crop yield declines is grass invasion.

In summary, advocates of the conventional model agree on a core set of proposals:

1. Tropical swidden crop yields are a reliable index of the robustness of the soil nutrient stocks of cultivated fields.
2. After the second year of swidden cultivation, the precipitous decline in crop yields reflects a commensurately precipitous decline in field nutrient stocks.
3. During cultivation, field nutrient stocks decline largely because they leach from soils during rainfall. Slashing and burning fertilizes fields with nutrients in the form of ash. With each season of cultivation, the soil nutrient stocks of fields progressively decline.
4. After two years of cultivation, soil nutrient stocks become so depleted that the field must be fallowed—a

process that replenishes field nutrient stocks through reforestation.

5. Weeds invade cultivated fields because they are better adapted to nutrient-poor environments, and the soils of fields cultivated for two years or more are highly nutrient-poor. In a relationship that is poorly understood, weed invasions contribute to or complement the decline in soil nutrient stocks, which is a primary cause of crop yield declines.

The conventional model of tropical ecology contradicts several key propositions of Boserup's cultivation lengthening model. For example, Boserup proposes that under extensive bush fallow cultivation farmers *chose* not to cultivate fields more than two years in a row, although they can cultivate fields for as many as eight years sequentially if obliged to do so by mounting population pressure. In contrast, the conventional model of tropical ecology posits that farmers *cannot* cultivate fields for more than two years in a row because of insurmountable ecological obstacles—e.g., depleted soil nutrient stocks and weed invasions—that make further cultivation impossible. Similarly, advocates of the conventional model of tropical ecology propose that in the absence of plowing or irrigation technologies or chemical fertilizers, swidden farmers who wish to intensify can do so only by shortening the fallow period. When in response to mounting population pressure farmers reduce the fallow period to less than the 6–10 year minimum, fields convert to grasslands and the productive capacity of the land is dramatically reduced. Boserup, in contrast, proposes that an alternative course of intensification is available—intensive bush fallow cultivation—which does not in the short term lead to field degradation. Whether farmers engage in intensive bush fallow cultivation depends primarily on their willingness to make the necessary labor investments in field preparation and maintenance that this system requires (Boserup, 1965, pp. 48, 53).

For decades, the principal proposals of the conventional model of tropical ecology were so broadly accepted that they were seldom questioned or scrutinized. The assumed nature of the ecological dynamics of tropical swidden agriculture prevented proponents of the conventional model from identifying the causes of crop yield declines after the second year of cultivation. Researchers asked, “Why do field nutrient stocks decline after the second year of cultivation?” Yet as scientists now realize, it would have been more productive to ask: “Do field nutrient stocks decline after the second year of cultivation, and if so, why?” Field nutrient stocks do decline under tropical swidden agriculture, but in the short term they do not decline enough to adversely affect crop yields. This finding, supported by recent research, has important ramifications for Boserup's proposal about cultivation lengthening and for archaeological

models of ancient Maya agricultural intensification processes.

The new model of the ecological dynamics of tropical agriculture

The new model of tropical ecology (and the model of the ecological dynamics of tropical swidden agriculture that it implies) rests on several core proposals that contradict those of the conventional tropical ecology model. Advocates of the new model conclude that the conventional model exaggerates the rate and amount of nutrient loss. The principal cause of post-second-year crop yield declines is not soil nutrient loss. Except in fields where farmers have reduced the fallow period too much, fields abandoned to fallow after two or more years of cultivation usually reforest rapidly. Such rapid reforestation is not consistent with the conventional model's hypothesis of soil nutrient depletion, suggesting that even after several years of cultivation field nutrients stocks remain robust. Indeed, recent studies suggest that at the point where most fields are abandoned for fallow, their nutrient stocks are richer than those of fallowing plots and mature forest (Brubacher et al., 1989, p. 165; Jordan, 1989, pp. 83–84; Sanchez, 1976, p. 377). The thesis that post-second-year crop yields decline because of field nutrient declines is not persuasive.

The new ecology model, which rejects all five of the core proposals of the conventional tropical ecology model, proposes the following, revised picture of field nutrient dynamics. When a plot of land is under forest and is fallowing, the nutrient stock of that plot resides both in the forest vegetation (calcium, magnesium, and potassium) and in the soil (nitrogen and phosphorus). When that forest is felled and burned and the plot planted with cultigens, much of the nutrient stock during the first or second year of cultivation is transferred to cultigens. Unfortunately for farmers, many weeds are better adapted than cultigens to the disturbed, light-rich conditions presented in open, deforested fields (Norman, 1979, p. 115; Tilman, 1988). In plots of tropical land cultivated under long and short fallow systems of agriculture, soil seed banks contain abundant weed seeds (Nepstad et al., 1996, pp. 29–30; Purata, 1986, p. 273). Although weeds are weakly competitive under forested, light-poor conditions where the soil surface is occupied by an already active root mass (Norman, 1979, p. 115), once the forest and its root mat are removed for agriculture, weeds thrive and readily outcompete slow-growing cultivated annuals. Consequently, with each successive year of cultivation, weeds absorb and sequester a progressively greater portion of the field's total nutrient stocks. Especially after the second year of cultivation weed growth in fields has two important negative impacts on cultivation. First, because weeds outcompete cultigens for the nutrients present in fields,

as weed growth becomes more prolific, progressively less nutrients are available to cultigens. Cultigens adapt to conditions of reduced nutrient availability by reallocating nutrients to the vegetative rather than the reproductive part of the plant (Tilman, 1988). For example, maize plants produce smaller or fewer ears, which is decidedly disadvantageous to the farmer (Arnason et al., 1982; Lambert and Arnason, 1980, 1986; Lambert et al., 1980). Crop yields decrease as weed biomass increases. Weeds function as a nutrient sink. In tropical environments with nutrient-rich soils, such as most of Central America (including the southern Maya lowlands), post-second-year crop yield declines are caused not by nutrient leaching, which does not occur at the scale envisioned by the conventional ecology model, but because of competition from weeds: weeds absorb key nutrients more rapidly and efficiently than cultigens (Sanchez, 1976, pp. 372–373). After two years of cultivation, most of the robust nutrient stocks still present in fields reside not in cultigens or forest vegetation but in weeds.

Humans can reduce the competitive advantage of weeds over cultigens, and thus facilitate crop growth, by destroying the weeds that compete with cultigens for nutrients. This they can accomplish through the use of herbicides, through plowing (uprooting weeds and burying them using a labor-efficient technology), or by digging up weeds by hand, usually with a hoe. This highlights a second negative impact of weed growth on cultivation. In pre-industrial societies, in which herbicides and plow technology are not available, farmers can control weed growth and thus cultivate fields for more than two years in a row only through very labor-expensive practices, such as intensive weeding.

For farmers who wish to intensify production by cultivating fields for more than two years, intensive weeding has two important advantages. First, removing weeds enables cultigens to absorb nutrients that otherwise would be sequestered in weeds. Weed removal allows cultigens to prosper. Second, weeds constitute a "green manure" nutrient bank that can be recycled to fertilize soils for cultivation. For farmers to extend the cultivation period beyond two years, farmers must: (1) weed intensively and (2) mulch fields with the vegetation that they pull from the ground during weeding (as well as with other materials). Mulching frees for cultivation the nutrients that otherwise would be sequestered in weeds. Intensive weeding and weed mulching are key elements of cultivation lengthening through intensive bush fallow cultivation.⁵

The opportunities for intensification through intensive weeding and weed mulching are essentially what

⁵ Soil nutrient recycling is an important component of many fallowing regimes. What distinguishes tropical intensive bush fallow cultivation is soil nutrient recycling with the objective of lengthening the cultivation period to six or eight years.

Boserup's model of intensification through intensive bush fallow cultivation predicts. Farmers lengthen the cultivation period by manipulating the same ecological process that makes forest fallow cultivation and extensive bush fallow cultivation possible: soil nutrient recycling. Under forest fallow and extensive bush fallow cultivation farmers free the nutrient contents of the

woody biomass and move it into soils by cutting and firing the forest or fallow. Under intensive bush fallow cultivation, they recycle the nutrient stocks stored in weeds not by cutting and burning the weeds—which is an inefficient and wasteful means of recycling the nutrient contents of weeds—but by: (a) pulling or digging them out by the roots before they seed and (b) manuring or

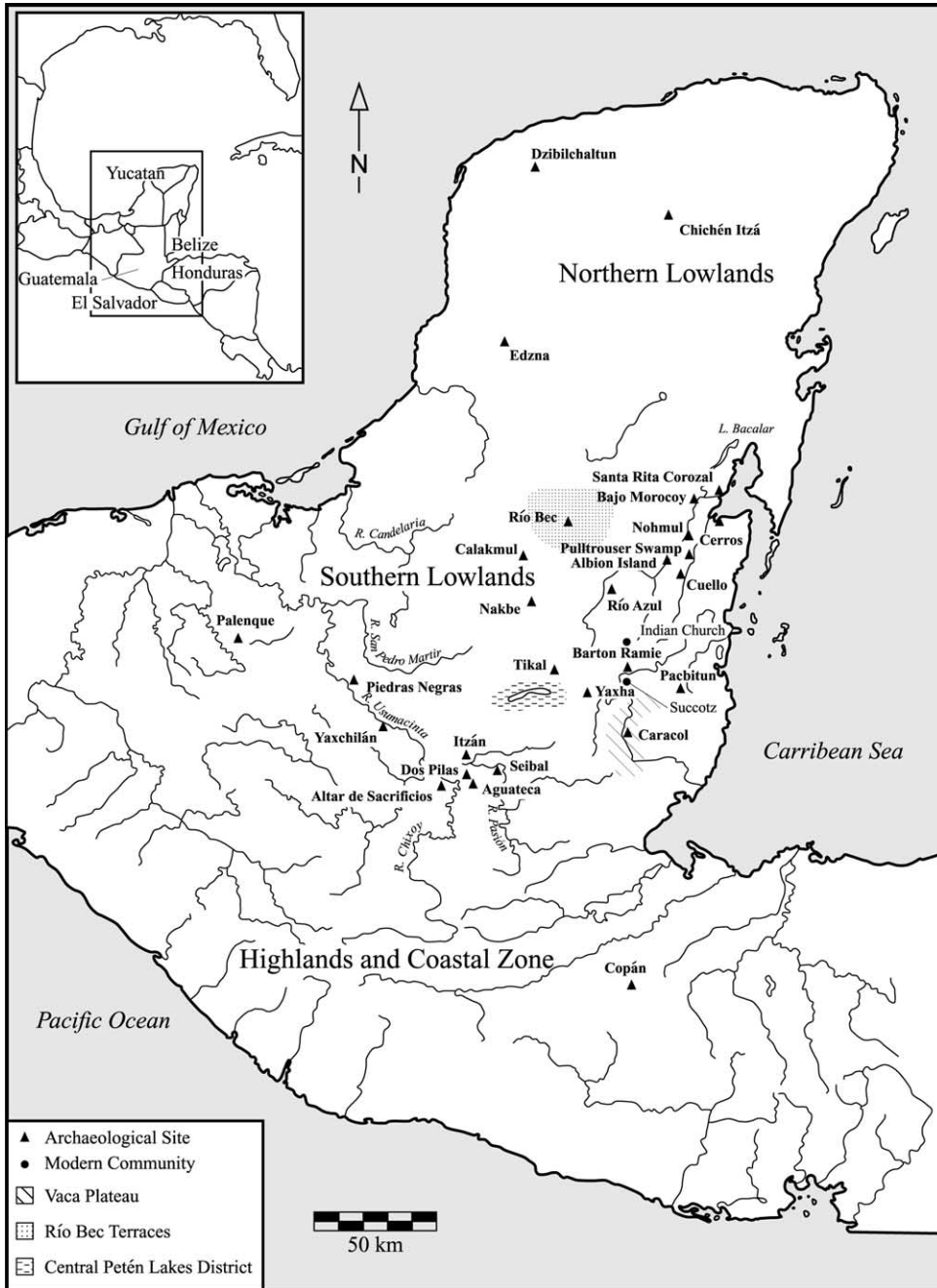


Fig. 1. Map of the Maya lowlands showing archaeological sites mentioned in the text.

composting them, either by laying them directly on the topsoil or by burying them beneath a shallow layer of topsoil. The new model of tropical ecology provides independent empirical support for Boserup's model of cultivation lengthening (1965, pp. 25–26), which predicts that to cultivate fields beyond two years in a row, farmers must enrich their nutrient stocks by mulching them with leaves, vegetable materials brought to cultivated plots from surrounding bush land, green manures, and composts, and through intensive weeding.

What are the implications of Boserup's model of tropical swidden intensification for archaeological investigations of the relationship between Classic Maya population growth, agricultural change, and anthropogenic environmental change? In the discussion that follows I review what archaeologists currently know about Classic-period Maya population growth and density trends, agricultural intensification, and the causes and consequences of the ninth-century southern Maya agricultural, demographic, and cultural collapse. Cultivation lengthening, I conclude, was an intensification strategy probably employed by some high-density southern lowland populations as a response to rising food production demands.

The Classic-period southern lowland Maya

Southern Lowland Maya chronology and demography

Archaeologists divide the lowland Maya into two groups on the basis of cultural and environmental criteria: the northern lowland Maya, who occupied the semi-arid limestone plains of Mexico's Yucatan Peninsula; and the southern lowland Maya, who occupied the considerably wetter moist tropical forests of Belize, northern Guatemala, and western Honduras (Fig. 1). Complex society emerged throughout the lowlands during the Preclassic Period (600 B.C. to 250 A.D.) and became highly elaborated during the subsequent Classic Period (A.D. 250–800). It was largely in the southern lowlands during the Late Classic (A.D. 550–800) that the Maya most fully developed the cultural achievements—including a hieroglyphic writing system, calendar system, and royal art—for which they are renowned. When the Maya collapse transpired during the Terminal Classic Period (ca., 800 to 900 A.D.) it primarily impacted Maya society in the southern lowlands. Most sites in the northern lowlands and many in northern and coastal Belize were not directly affected by the collapse, and indeed many prospered through the subsequent Postclassic Period (A.D. 900 to ca. 1520), which ended with the Spanish arrival. The southern lowland Maya of the Late Classic period present an important case study in long-term population-agriculture interactions in the humid tropics.

Archaeologists reconstruct southern lowland Maya demographic trends, including spatial and chronological variations in population size, density, and composition, from settlement and other data collected at dozens of urban centers and their rural sectors (Ashmore, 1981; Rice and Culbert, 1990; Tourtellot, 1993). To devise reliable population estimates, archaeologists require representative samples of settlement in rural areas, where the vast majority of the ancient Maya—commoner farmers—resided. The principal southern lowland sectors whose rural settlement archaeologists have surveyed to date include the following (Fig. 1): Tikal's 104 km² Sustaining Area, surveyed by Puleston (1974, 1983), Haviland (1965, 1970), and Carr and Hazard (1961); Ford's (1986) survey of a 28 km-long transect between Tikal and Yaxha; Don Rice's survey of the Central Petén lakes district, which examined transects centered on lakes Sacnab, Yaxha, Macanche, Salpeten, Petenxil, and Quexil (Rice, 1976; Rice and Rice, 1990); Seibal's rural hinterland, surveyed by Tourtellot (1988, 1990); and the Belize River Valley, surveyed by Willey (Willey et al., 1965) and Ford and Fedick (Fedick and Ford, 1990; Ford, 1990; Ford and Fedick, 1992).⁶ Outside of what Mayanists call the "central zone" (Hammond and Ashmore, 1981, Fig. 2.1)—roughly defined by Río Bec and Becan on the north, Lake Petén-Itzá on the south, the Belize River Valley on the west, and the headwaters of the Río San Pedro Martir on the west—rural settlement patterns (and thus Classic-period population densities) remain poorly known (Sharer, 1994, p. 341), with the exception of the Copan Valley, which Webster, Sanders, and others (Webster, 1985; Webster and Freter, 1990; Webster et al., 2000; Webster and Gonlin, 1988; Webster et al., 1992) very intensively surveyed. Regions whose rural zones have not yet been extensively surveyed include most of the western lowlands (along the Río Usumacinta), most of the southwestern lowlands (along the Río de la Pasión and vicinity [with the exception of Seibal]), and much of the southeastern lowlands (in Guatemala, southeast of Lake Petén-Itzá and west of Belize).⁷

⁶ In this paper I use the term "southern lowlands" to refer to the ecologically distinct area of northern Guatemala, southern Campeche and Quintana Roo, and Belize that supports a moist-to-wet lowland tropical forest. The term does not include Copan in the Honduran highlands, which has a very different environmental setting. For this reason I do not include the Copan Valley in my list of southern lowland sectors whose rural settlement has been surveyed by archaeologists.

⁷ Archaeologists have surveyed or currently are surveying rural settlement in several of these areas (e.g., the Petexbatún region, rural Piedras Negras, and in Belize, La Milpa and surrounding rural areas as well as the Sibun River valley), but those data have yet to be published.

To reconstruct past population trends Mayanists employ a “house count” procedure, wherein they clear the forest floor of vegetation to locate visible house mounds, count and date those mounds or some sample of them, then multiply the periodized subtotals by a constant thought to represent the average size of an ancient family (Turner, 1990). To achieve an unbiased estimate, many factor into the equation a variety of mathematical corrections, including the estimated percentage of non-dwelling structures, the estimated percentage of dwelling structures not occupied during specified time periods within archaeological phases, and the estimated percentage of dwelling structures not counted during surface survey because they are buried (Johnston, 2002). The product of the equation is the “total population” of a site or region. Population reconstructions figure prominently in archaeological explanations of Maya cultural development, including analyses of the causes of the ninth-century Maya collapse (Culbert, 1988; Rice, 1993; Sanders and Webster, 1994; Santley et al., 1986; Turner, 1989, 1990).

Estimated Late Classic Southern Maya population size and density

From settlement data collected at more than 15 sites and inter-site regions detailed population trends have been reconstructed (Rice and Culbert, 1990, pp. 22–35; Rice and Rice, 1990, p. 146; Turner, 1989; Webster et al., 1992; Whitmore et al., 1990, p. 35). Particularly comprehensive is the estimate proposed by Turner and his colleagues (Turner, 1989, 1990; Whitmore et al., 1990) of gross population growth trends within the central zone, which they define as a roughly 100-km wide corridor that passes from southern Campeche and Quintana Roo, Mexico, into north-eastern Guatemala, and centers on the archaeological sites of Río Bec, Calakmul, and Tikal (Fig. 1). This 23,000 km² cultural heartland, which constitutes approximately 10% of the total Maya lowlands, during the Late Classic was perhaps the most densely occupied area of the southern lowlands. Their admittedly crude periodized population estimates for this region’s

urban and rural areas (Table 2) reveal annual positive growth rates ranging from 0.24% per year during the fourth century to 0.2% during the eighth (Turner, 1989, p. 189). These growth rates, which fall well within the range typical of non-industrialized agrarian societies, resulted in steady population increases. The highest population growth rates—estimated at 0.6% per year—occurred during the ninth century, shortly before the collapse (Whitmore et al., 1990, Table 2.4).

In almost all rural sectors surveyed by archaeologists, Late Classic populations on arable land were remarkably dense. Culbert et al. (1990, pp. 116–117) calculate that in the rural periphery of Tikal—defined as a circle enclosing 314 km², which does not include the site’s urban center or its extensive surrounding “suburban” districts—on average 153 persons inhabited each square kilometer (including *bajos*) during the Late Classic period. Late Classic population densities in the rural periphery of Seibal are roughly comparable: 144 persons km² (Tourtellot, 1990, pp. 30–31). In the Central Petén lakes district, rural population densities of the same period are considerably higher: on average 191 persons km² (Rice and Rice, 1990, p. 143). For the Belize River Valley, Ford (1990, p. 180) documents non-periodized structures (rather than persons) per km². These densities range from 200 structures per km² in the fertile uplands to 104 per km² in the valley alluvium, for an average of 118 structures per km²—a number that compares favorably to the number of non-periodized structures per km² along the 28 km-long transect between Yaxha and Tikal: on average 110 structures per km² in all types of terrain, including uninhabitable swampland. (Scarborough et al. (1995, pp. 101–102) report similarly high structure densities in and around La Milpa, Belize.) Although Ford’s structure densities for the Yaxha-Tikal transect are not periodized, 92% of those tested contain Late Classic ceramics (Ford, 1986, p. 62), indicating that most were occupied during this period. Her non-periodized rural structure counts are similar to those obtained elsewhere (cf. Culbert, 1988, Table 4.3). From these data archaeologists conclude that Classic-period densities were high throughout the central zone and in several other areas of the southern

Table 2
Central Maya lowlands population reconstruction, 300 BC–AD 1000 (after Whitmore et al., 1990, p. 35)

Date	Population	Density (people/km ²)	Annual rate of change (%/yr)
300 BC	242,000	10.6	+0.06
300 AD	1,020,000	44.9	+0.24
600	1,077,000	47.4	+0.02
800	2,663,000/3,435,000	117.2/151.2	+0.45/0.58
1000	536,000	23.6	–0.80/0.93

lowlands.⁸ Urban population densities were considerably higher, ranging from 500 to 800 persons per km² at many sites (Culbert and Rice, 1990, p. 20; Rice, 1993, Table 1) to more than 1000 per km² at the most densely settled centers (Chase and Chase, 1998, p. 62; Webster and Freter, 1990, p. 51).

It should be cautioned that large areas of the southern lowlands remain unexplored and unsurveyed (Sharer, 1994, p. 341), and so archaeologists cannot safely assume that population densities were uniformly high across all the Maya area. Indeed, I suspect that in some southern lowland zones (including areas north and south of the hills that flank the banks of the Río de la Pasión) population densities may have been moderate or low. Outside the central zone, in other words, population densities might have been characterized by considerable spatial heterogeneity. Moreover, not all archaeologists agree with these population reconstructions (although most do). Webster (2002, pp. 174, 264) and Ford (1991), for example, regard current estimates of Maya population size and density as greatly over-inflated.

In any case, archaeologists' density estimates translate into very substantial total populations in some areas. Archaeologists propose that the largest urban centers had total populations ranging from 40,000 (Culbert et al., 1990, p. 117) to perhaps 150,000 (Chase and Chase, 1996, p. 805). The population of the Tikal polity alone was more than 400,000 (Culbert et al., 1990, p. 117). The Maya lowland central zone supported a maximum Late Classic population of not less than 2.5 million (Turner, 1989, p. 183; Whitmore et al., 1990, Table 2.4) and perhaps twice that (Sanders and Webster, 1994, p. 84). Population estimates raise the question of economy and intensification: Where population densities were high, how did such large numbers of people provide for themselves agriculturally?

Maya population growth and agricultural intensification

As the Maya population grew, progressively greater demands were placed on the agricultural foundation of their economy. Archaeologists propose that as population density increased, the Maya responded agriculturally in the manner predicted by Boserup's five-part evolutionary model and by the conventional model of tropical ecology (1965)—they increased food supply by intensifying production, and they intensified production by shortening the fallow period (e.g., Rice, 1978; Sanders, 1973; Turner, 1989). To keep pace with growth, farmers first extensified production by colonizing and deforesting for agriculture unoccupied and under-occupied terrain, much of which may have been located be-

tween emerging centralized polities and along the lowland margins. During this stage most Maya practiced forest fallow cultivation. As the land filled with farmers, opportunities for extensification were exhausted, and the Maya increased production through technological innovation and crop cycle intensification (reduction of the fallow period). Many Maya then turned to extensive bush fallow cultivation. (Other strategies of economic adaptation included craft production and exchange). By the seventh or eighth century A.D., most rural households had adopted a complex, geographically variable, and highly productive mixture of agricultural techniques (Dunning et al., 1998). Depending on local ecological conditions and resource needs, these would have included kitchen gardening, orcharding, multi-cropping, small-scale agro-forestry (Wiseman, 1978, pp. 85–89), fertilizing fields and gardens with night soils and organic trash (Ball and Kelsay, 1992; Dunning et al., 1997; Harrison, 1993, p. 84; Killion et al., 1989; Santley et al., 1986, p. 134), farming colluvial soils along *bajo* margins (Dunning et al., 2002), field water management strategies (Dunning et al., 2002, p. 276; Fedick et al., 2000; Lohse and Findlay, 2000; Scarborough, 1993; Scarborough et al., 1995), and a form of intensive cultivation recently described by McAnany (1995, pp. 68–79) as fixed-plot, variable-fallow swidden (Fedick, 1996; Flannery, 1982; Harrison and Turner, 1978; Rice, 1993). The latter corresponds roughly to Boserup's extensive bush fallow cultivation intensified through fallow reduction.

Were these agricultural technologies sufficiently productive to support the Late Classic population densities estimated from settlement data? Advocates of the traditional model of Maya agricultural intensification conclude that as pressure on resources increased because of population growth, farmers intensified outfield agriculture in the only manner available to them: they progressively shortened and perhaps eventually eliminated the fallow period. Yet given its damaging anthropogenic effects, including soil fertility loss, field weed invasions, and topsoil erosion, would progressive fallow reduction have been a sustainable intensification strategy?

Sanders (1973) and Rice (1978, 1993) have closely examined these issues. They propose that particularly dense populations of Late Classic Maya may have intensified production to the point of what they call "bush swidden" cultivation, characterized by a crop-to-fallow ratio of 1:3 (Boserup's extensive bush fallow cultivation intensified through fallow reduction), or "grass swidden" cultivation (Boserup's "short fallow" system), characterized by a crop-to-fallow ratio of 1:1. They conclude that neither system would have been sustainable for long because of their anthropogenic effects. Moreover, neither archaeologist is sure whether either system would have supported Late Classic populations during the period of their greatest density (Culbert, 1988, p. 95)—a doubt also expressed by Scarborough

⁸ In the Copan Valley of highland Honduras, Late Classic maximum population density relative to arable land was similarly high (Sanders and Webster, 1994, p. 93).

(1993, pp. 25–26). Sanders (1973, Table 22) posits that maize-based bush fallow cultivation intensified by reducing the fallow period to about six years could have supported approximately 100 people per km². This is well below the 180 person/km² estimated to be the average Late Classic population density of southern lowland rural zones (Rice and Culbert, 1990, p. 19). If one assumes (as seems reasonable) that the Maya had tribute obligations and only 50% of the land was cultivable (because of the presence of non-arable landscape features, including *bajos* and areas of poor soils), the estimate must be reduced to about 50 persons per km². Similarly, maize-based non-plow grass fallow (wherein farmers cultivate for one or two years and then fallow for an equivalent period) might have supported approximately 154 people per km², but when similar assumptions about tribute and land usability are applied the estimate is reduced to about 75 persons per km² (Sanders, 1973, Table 22). Turner's (1976, Table 1) estimates are comparable: 25 persons per km² for bush fallow, 75 persons per km² for grass fallow.

If Sanders and Turner are correct—and it is possible that their estimates are not correct (a recalculation of the carrying capacities of various fallowing regimes in the Maya lowlands is long overdue)—the populations of several areas of the southern lowlands would have surpassed the carrying capacities of bush fallow and grass fallow cultivation a century or more prior to the ninth-century collapse. In fact, Rice (1978, Table 4.8; 1993, pp. 41–42) estimates that had they relied on either of these forms of cultivation, the population of the central Petén lakes region would have surpassed carrying capacity during the seventh or eighth centuries A.D., as also occurred in the Copan Valley of Honduras at about the same time (Sanders and Webster, 1994, p. 93; Webster, 1999, p. 30; Webster et al., 1992, pp. 196–198). Yet according to the reconstructions of Whitmore et al. (1990, p. 35), this was a period of sustained and continuous population growth. For many archaeologists, this alleged disjunction between population density and food producing capacity is an important research issue and a possible key to the Maya collapse. What other methods of intensive agriculture might the Late Classic Maya have employed to cope with increasing food demands?

Maya terraced-field agriculture

One method of intensification that the Classic Maya are known to have employed is terraced-field agriculture. Curiously, many agricultural terraces were constructed and worked during the Late Classic population maximum, but few were constructed by the densest southern lowland populations. Did the Maya construct terraced-field systems in response to population growth, and did terraced-field systems relieve Late Classic-era population pressure on resources?

As Kirch (1994, p. 19) and others (see Leach, 1999, pp. 311–316) observe, farmers intensify production either through crop cycle intensification (e.g., fallow reduction or cultivation lengthening) or through landesque capital improvements (e.g., terraces, irrigation canals, raised fields). The Maya did both. The most widely employed landesque capital improvement was terracing, whose principal function was to control the loss of topsoil from slopes through erosion. Terraces do not prevent soil detachment; instead they slow runoff velocity and decrease rate of sediment transport by reducing slope length and gradient (Lal, 1990). Terraces are found in only a few regions of the southern lowlands, and their construction style, individual sizes, and total area of coverage vary between regions.

At the modest end of the spectrum are terraces constructed in the Petexbatún region of Guatemala (near Dos Pilas and Aguateca—Fig. 1), most of which are small constructions found in and around rural residences (Beach and Dunning, 1995; Dunning and Beach, 1994; Dunning et al., 1997). There is little evidence of agricultural terracing at nearby Dos Pilas (Houston, 1993), Seibal (Tourtellot, 1988; Willey et al., 1975), or Itzán (Johnston, 1994), suggesting that within the Río de la Pasión region terraced-field agriculture was a small-scale, localized practice.

Considerably larger and more spatially extensive are the agricultural terraces built to retain shallow upland soils (Turner, 1983, pp. 84, 87) in rural sectors of the Río Bec region of the Yucatan Peninsula (Turner, 1978, 1983).⁹ Other terraces—all located in areas that in antiquity would have been rural zones distant from substantial urban centers have been recorded 40 km southeast of Tikal (Turner, 1978, p. 168), in savannas south of Lake Petén-Itzá (Rice, 1993, p. 37–38), and across an area of Belize's Vaca Plateau reported to be 400 km² in size (Turner, 1979, p. 106). Poorly documented terraces have been observed in the Poptun and Dolores areas of Petén, Guatemala (Turner, 1979, p. 106). Like the Petexbatún terraces, those of the Río Bec region functioned as sediment traps, creating behind their low stone walls narrow and shallow planting surfaces (Beach and Dunning, 1995; Turner, 1983, p. 73).

The most robust terraces currently known in the Maya lowlands are those at Caracol (Chase and Chase, 1998; Healy et al., 1983). Covering an area of at least 17 km², and built primarily during the early part of the Late Classic, when urban population densities at the site averaged 1036 persons per km² (Chase and Chase, 1998), these large bench terraces transformed almost all of

⁹ Although Turner (1978, p. 168) proposes that some 10,000 km² of the Río Bec region is terraced, Sanders (1979, p. 495) questions this figure, noting that the estimate is based on a limited number of intensive surveys and some spot checks along highways.

Caracol's hilly terrain on a massive scale. The Caracol constructions are not mere sediment traps. Rather they transform slopes highly susceptible to erosion into a series of broad, deep-soiled, and highly stable agricultural surfaces that, with proper fertilizing and maintenance, could be intensively cultivated (Chase and Chase, 1998). Extensive terrace networks also have been documented near Xunantunich (Dunning et al., 1998, p. 94) and La Milpa (Dunning et al., 2002, p. 276), both in Belize.

Most terraces at Caracol, La Milpa, and in the Petexbatún and Río Bec regions were used and perhaps constructed during the Late Classic period, when southern lowland population size and density was at its maximum.¹⁰ By stabilizing slope topsoils, terraces allowed farmers to cultivate plots more frequently than would have been possible on non-terraced, erosion-prone slopes. Yet Maya farmers did not construct terraces with the primary objective of increasing productivity, defined as increased returns per person-hour of labor input. Instead, they terraced to *prevent decreases* in productivity, which surely would have occurred if cultivated topsoils had been allowed to erode. Prior to constructing terraces during the Late Classic period, the Maya perhaps had intensively cultivated some sloped topsoils for some time. Cultivated tropical soils undergo structural changes—declines in organic matter, reduced biotic activity and permeability, and increased compaction, leading to accelerated runoff—that increases the risk of soil erosion (Lal, 1986, pp. 30–35). The removal of forest cover for agriculture adds to that erosion risk. Moreover, southern lowland topsoils are thin (on average 20–50 cm [see Johnston, 2002, pp. 21–27]) and underlain by compact clays inappropriate for agriculture. Had these topsoils eroded, fields would have been ruined rapidly and productivity seriously compromised. Terracing stabilized but did not greatly increase productivity at the cost of substantial initial construction and thereafter increased annual per capita labor inputs. (In many areas, some Maya undoubtedly constructed terraces long before the onset of intensification-induced slope erosion associated with maximum population density.) In most cases the construction of terraces would not have significantly increased per capita productivity and thus the practice of terraced-field agriculture would not have constituted an effective long-term solution to the problem of decreasing resource availability.

¹⁰ That the Late Classic Maya were not the first to build agricultural terraces is demonstrated by the recent discovery by Richard Hansen and his colleagues (Hansen, 2000, 50–68; Dunning et al., 2002, p. 6; Martinez et al., 1999) at Nakbe, a massive Preclassic center, of mud terraces erected during Late Middle Preclassic and Late Preclassic periods. Geological analysis reveals that farmers maintained the fertility of Nakbe's terraces by mulching them with nutrient-rich mucks mined from nearby *bajos*, or large areas of seasonally flooded, low-lying terrain (Dunning et al., 2002, p. 276).

Perhaps for this reason, the densest Late Classic southern lowland populations apparently did not adopt terraced-field agriculture as an intensification strategy during the era of decreasing per capita resource availability. Many southern lowland agricultural terraces were constructed not near densely populated ceremonial-urban centers, as would be expected had they been constructed in response to population growth, but in rural zones with relatively modest population densities. Some of those built in the Río Bec hills and Belize's Vaca Plateau were so distant from known ceremonial centers and polity capitals that it is possible that the populations who worked them were not directly subject to the political and economic demands and influences of kings or royal courts.

Agricultural terraces are expensive to build and maintain (Turner, 1983, pp. 108–111), and as such they exemplify not only technological innovation but also substantial productive intensification (measured as increased per capita labor inputs per unit of cultivated land). As Boserup (1965, 1981) notes, farmers intensify production through terrace construction and other means only when two conditions are met: (1) when because of population pressure, extensification (which is less labor-intensive) no longer is possible; and (2) when farmers are experiencing or anticipate significant resource stress. Maya farmers living in rural zones distant from ceremonial centers did engage in terrace agriculture to relieve resource stress, but it appears that in most cases the locus of that stress was local and rural rather than distant and urban. The known spatial distribution of terraced fields suggests that with few exceptions terraced-field agriculture was not practiced to relieve pressure on resources in the most densely populated sectors of the southern lowlands. Indeed, some rural farmers may have practiced terraced-field agriculture to increase surpluses and thus reduce the risk of starvation during periodic episodes of lower-than-average rainfall.

Raised- and drained-field agriculture

Two other highly productive and intensive agricultural methods practiced by southern lowland peoples are raised- and drained-field cultivation. Did the Late Classic Maya widely engage in raised- and drained-field agriculture as an intensification response to population growth? The archaeological evidence suggests that they did not.

As with agricultural terraces, the geographical distribution of raised- and drained-fields is highly restricted (Fig. 1). Despite initial claims that the Maya constructed raised fields throughout much of the southern lowlands (Adams, 1983; Adams et al., 1981; Siemens, 1982), definitive evidence of this activity has been found at only a few locations (Pope and Dahlin, 1989): the Pulltrouser Swamp and Albion Island areas of northern Belize (Harrison, 1993; Pohl, 1990; Turner and Harrison,

1983); Bajo Morocoy of southern Quintana Roo (Gliessman et al., 1983; Harrison, 1993, pp. 108–111); Río Azul in northern Guatemala (Culbert et al., 1990); and south of La Milpa, Belize (Dunning et al., 2002, p. 280). With the exception of Río Azul and La Milpa, most of these zones are located along the margins of the Maya lowlands, in some cases in terrain that supported (relative to those of the densely packed central zone) populations of only modest density. In the central zone, Culbert, Fialko, and others (Culbert et al., 1996; Fialko and Culbert, in press; Kunen et al., 2000) report drained-field-like constructions in *bajos*, or seasonal swamps, south of Tikal, but these appear to be modestly-sized constructions that modified only small areas.¹¹ South of the central zone, along the Río de la Pasión, radar imagery suggested to Adams (1983) the presence of raised-field systems, but recent ground-truthing reveals that these features are not agricultural (Dunning et al., 1997, pp. 258–259).

The lack of extensive raised and drained-field systems in the densely settled central zone of the southern lowlands is surprising for several reasons. First, according to current archaeological models, these populations were experiencing potentially significant resource stress, which should have motivated them to intensify production using these or other practices. Second, because of their density, these populations had the labor resources needed to construct and cultivate raised- and drained-field systems. Third, many of the largest population centers occupied hills that overlooked *bajos* appropriate for raised- and drained-field agriculture (Adams et al., 1981). Indeed, as much as 30% of the northern sector of the southern Maya lowlands [i.e., the “central zone” (see above)] is covered by *bajos* (Scarborough, 1993, p. 23). In other words, central zone populations had the natural and labor resources needed to undertake raised and drained-field systems, they had an appropriate motivation, and undoubtedly they were familiar with these methods of intensification, yet few if any adopted them.¹²

Also inconsistent with the thesis that the Maya adopted raised- and drained-field agriculture as an intensification response to increased population pressure on resources is the timing of the initial construction of raised-field systems (Don Rice, personal communication, 2001). According to Boserup’s (1965, 1981) model of progressive agricultural intensification and Brookfield’s (1972) modification of it, the Maya should have engaged

in raised- and drained-field agriculture for subsistence purposes only when population growth required them to do so—that is, when the carrying capacities of less labor-intensive practices (for example, extensive bush fallow cultivation and non-plow short fallow cultivation) had been surpassed. Yet in northern Belize, where extensive raised fields systems exist, the Maya first constructed raised fields not during the Late Classic, when population densities were at their peak, but during the Preclassic era (Pohl, 1990, p. 402; Pope et al., 1996, p. 172), when local population densities were low enough to have been readily supported by much less labor-intensive practices.

If not required to do so by population pressure on resources, why did Preclassic northern Belize populations undertake agricultural practices whose labor requirements, according to Devevan (1982, Table 1) and Webb (1993, p. 694), were approximately 30–100 times the annual requirement for areas under swidden cultivation? A possible answer is supplied by Brookfield (1972, p. 38), who points to ethnographically documented low-density populations that engage in intensive agricultural practices to meet the requirements of “social production” (“goods produced for the use of others in prestation, ceremony, and ritual”) rather than “production for use,” or subsistence production (production for auto-consumption by the grower, his family, and immediate associates”). Social production is rarely motivated by population pressure on resources (Brookfield, 1972; Kirch, 1994, p. 17). Alternatively, rural farmers may have practiced raised-field agriculture as a risk reduction strategy.

In summary, the fact that raised-field agriculture was practiced at Río Azul and in a *bajo* south of Tikal (both located in the central zone) suggests that dense central zone populations knew of raised- and drained-field forms of agriculture but (with few exceptions) chose not to undertake it. Instead, several populations opted to cultivate colluvial deposits along the margins of *bajos* (Dunning et al., 1999, 2002; Scarborough et al., 1995). The choice is surprising given that by the end of the Late Classic period several central zone populations evidently had passed the carrying capacities of other forms of intensive agriculture thought to have been practiced by the Maya, including non-plow short fallow and extensive bush fallow forms of cultivation (Rice, 1978, 1993; Sanders, 1973; Webster, 2002, p. 174). Assuming that archaeologists’ estimates of these carrying capacities are reasonable, three alternative explanations of the apparent disarticulation between estimated central zone population densities and reconstructed agricultural practices come to mind. First, current estimates of central-zone population density maxima are inaccurate, and so central populations were less dense than currently estimated (Ford, 1991; Webster, 2002, pp. 174, 264). Second, current estimates of central zone populations are accurate, and to cope with high maximum densities these

¹¹ In the northern lowlands, raised- and drained-field systems are found in the Río Candelaria drainage of Campeche (Siemens and Puleston, 1972), at Edzna (Matheny, 1978), and in Quintana Roo *bajos* (Harrison, 1978, 1982).

¹² Some central lowland populations did cultivate colluvial deposits (composed of soils eroded from surrounding hillsides) along the margins of *bajos* (Dunning et al., 2002), but this activity did not constitute raised- or drained-field agriculture.

populations engaged in forms of raised- or drained-field agriculture that leave no archaeological traces. Third, current population estimates are accurate, and to cope with rising densities some farmers engaged in forms of intensification other than terraced-field agriculture, raised- or drained-field agriculture, reduced fallow extensive bush fallow cultivation, and non-plow short fallow cultivation. One possibility is cultivation lengthening achieved through intensive bush fallow cultivation.¹³

The traditional explanation of the Maya collapse

The traditional explanation of the Maya collapse posits that to intensify swidden production, Maya farmers progressively shortened the fallow period, as a consequence of which, soil nutrients leached from cultivated soils and fields suffered weed invasions, insect infestations, and topsoil erosion. In the southern lowlands, corroboration of this collapse reconstruction is provided by paleoecological evidence of several important anthropogenic changes (Curtis et al., 1998; Deevey et al., 1979; Islebe et al., 1996; Leyden, 1987; Rice, 1993; Rice et al., 1985; Wiseman, 1985): (a) a progressive replacement of forest species with grasses, interpreted as an expression of deforestation for agriculture and a loss of woody species due to progressive fallow reduction; (b) a loss of key soil nutrients, including phosphorus and organic carbon, and their sequestration in lacustrine deposits, where they were no longer available to cultivators; and (c) an increase in topsoil erosion so significant that in many lakes it produced a layer of “Maya clay” difficult to penetrate even with sharp coring instruments (Binford et al., 1987; Curtis et al., 1998, p. 154; Rice, 1993, p. 29). At Copan (Sanders and Webster, 1994, pp. 99–101; Webster, 2002, pp. 312–316; Wingard, 1996, p. 229), Tikal (Olson, 1981), and in the Belize Valley (Willey et al., 1965), geological evidence reveals slope erosion caused by intensification. Rates of erosion, deforestation, and soil nutrient loss roughly paralleled increases in Maya population size and density (Rice, 1993, Fig. 8). As the agricultural environment degraded, advocates of the model propose, crop production suffered.

Judging from osteological data, the growing agricultural crisis caused a decline in the general well being among some (Rice, 1993, pp. 42–43; Santley et al., 1986, pp. 137–145) but not all (Danforth, 1994, 1997, 1999; Demarest, 2001; Glassman and Garber, 1999; White,

1997) Maya populations. In the central and southwestern Maya lowlands (Haviland, 1967, 1972 [but see Danforth, 1999]; Saul, 1972, 1973), at Pacbitun, Belize (White, 1994, 1997; White et al., 1993), and the Copan Valley (Sanders and Webster, 1994, p. 103; Storey, 1985, 1997, 1999a,b; Webster, 2002, pp. 316–317; Whittington, 1989, 1999), where Late Classic population densities were high and the anthropogenic effects of long-term intensive agriculture undoubtedly were keenly felt (Rice et al., 1985; Sanders and Webster, 1994), skeletal remains reveal nutritional stress. However, along the Río de la Pasión (parts of which were not intensively colonized until the seventh century A.D. (Demarest, 1997)), nutritional stress was less pronounced (Wright, 1997; but see Saul, 1972, 1973 and Willey et al., 1965), possibly because the anthropogenic effects of density-dependent agricultural intensification were less fully developed than elsewhere (perhaps indicating regionally variable population density).¹⁴ Resource stress encouraged inter-polity warfare (Demarest, 1997; Inomata, 1997; Webster, 1993, 1998, 2002, pp. 274–288), wherein elites competed for a degrading resource base. The primary causes of the collapse were not the same in all areas (Webster, 2002, pp. 260–294), and the collapse and the cultural changes that led to it had important political, economic, and ideological components that should not be underestimated (Adams, 1973; Demarest, 1992; Martin and Grube, 2000; Webster, 2002; Willey and Shimkin, 1973, p. 484).

That the Maya either could not intensify production sufficiently or could not sustain intensification is indicated by the Late Classic collapse, which, most archaeologists believe was in large part (but not exclusively) a population collapse precipitated by agricultural failure. Generally speaking, that failure is attributed to anthropogenic changes set in motion by productive intensification through fallow reduction. The key anthropogenic changes are of three types, and over time the significance attributed to these changes in explanations of the Maya collapse has shifted. Through the 1940s, many archaeologists, ecologists, and agronomists believed that the principal ecological catalyst of the collapse was the first change—weed invasion—(Cook, 1909, 1921; Emerson and Kempton, 1935; Lundell, 1933; Steggerda, 1941), while others proposed that the second change—declining soil fertility—played a more significant role (Cooke, 1931, 1933; Ricketson and Ricketson, 1937). Through the 1960s, the third change—topsoil erosion—was greatly favored (Cowgill, 1961, 1962; Dumond, 1961). Since then archaeologists have preferred models that find the roots of the collapse in the interaction of all three processes (Abrams and Rue, 1988; Abrams et al., 1996; Adams, 1973; Culbert, 1988; Dunning et al., 1999,

¹³ Alternatively, archaeologist’s estimates of maximum central zone population densities are correct but their estimates of the carrying capacities of reconstructed agricultural practices are not, in which case there was no disarticulation between population densities and agricultural practices. Few Mayanists have publicly considered this possibility.

¹⁴ Citing osteological data, Wright and Wright (1996) dispute the ecological model of the collapse.

p. 658; Hester, 1952, 1953a,b; Johnston, 1997; Sanders, 1973; Sanders and Webster, 1994; Santley et al., 1986; Webster, 2002, pp. 251–258, 327–348; Willey and Shimkin, 1973). Thus, the key anthropogenic changes are soil nutrient losses through leaching, weed invasions, and topsoil erosion caused by heavy seasonal rainfall on soils deforested for cultivation.

The collapse started in the late eighth century and gathered momentum through the ninth, its spatial progression marked archaeologically by a cessation of elite construction activities and the abandonment of all urban centers and most of their rural hinterlands (Culbert, 1973; Webster, 2002). That the timing of the collapse was spatially heterogeneous suggests that across the landscape a great variety of changes—political, economic, ideological, and social—contributed to and exacerbated the primary causes of the collapse (Sharer, 1994, p. 341; Webster, 2002, pp. 260–326).¹⁵ The severity of the collapse can be judged by its outcome—in many places an astonishing 90% population reduction in less than two centuries (Whitmore et al., 1990), after which much of the southern lowlands remained virtually abandoned for almost a millennium (but see Johnston et al., 2001). Whether the population collapsed through migration, increased mortality, or both is not known.

Underlying the traditional explanation of the Maya collapse is an important assumption that colonial agronomists devised (Cook, 1909, 1921; Jarosz, 1993) and ecologists until recently endorsed (Sanchez and Logan, 1992, p. 35): that in tropical settings, intensified swidden contains the seeds of its own inevitable destruction. This assumption serves as a foundation of the conventional model of tropical ecology. Although consistent with archaeological and paleoecological data, the traditional collapse explanation leaves unexplained how decades prior to the collapse some Maya populations evidently surpassed the carrying capacities of other available intensification strategies. One solution is to propose that some Maya increased agricultural production through intensive bush fallow cultivation, a strategy that would have temporarily but not permanently (see below) allowed high-density populations to avoid a food production crisis.

Agricultural intensification through cultivation lengthening: A model

The (a) traditional model of Maya agricultural intensification and its anthropogenic effects and (b) the

traditional explanation of the Maya collapse derived from settlement, epigraphic, and lake-core data are problematic in that both are founded on a model of tropical ecology, and more specifically, on a model of the soil ecology of tropical swidden agriculture, that many leading soils scientists and tropical ecologists no longer endorse. The problem is not unique to Maya archaeology: as Sanchez and Logan (1992, p. 35) observe, obsolete concepts about tropical soils continue to be cited even in major ecological texts. In this section I propose a general model of cultivation lengthening consistent with the new model of tropical ecology.

Tropical soil ecology and the Maya collapse

During the last century, agronomists, soil scientists, and ecologists have repeatedly attempted to determine why in swidden plots crop yields decline—sometimes substantially and precipitously—after the second year of cultivation (Sanchez, 1976). Modern Maya swidden agriculture exemplifies the problem. In Yucatan (Villa Rojas, 1969), northern Guatemala (Atran, 1993, p. 681; Cowgill, 1961, p. 10), and Belize (Lambert and Arnason, 1986), Maya crop yields after the second year of cultivation often decline to levels that are a mere 30% of first year yields (after falling during the second year to yields 70–85% of first year levels). The key proposal of the conventional model of tropical ecology—that fallow reduction exhausts the soil and robs it of its fertility (e.g., Kricher, 1989; Richards, 1952)—underlies the traditional explanation of the Maya collapse. The hypothesis has been remarkably long-lived despite the fact that from extensive data collected over the course of the last 40 years, soils scientists now conclude that it applies to only a few areas of the world, Mesoamerica not among them (e.g., Devevan, 1971; Harris, 1971; Jordan and Herrera, 1981; Nye and Greenland, 1964; Rattan Lal, personal communication, 2000).

Tropical ecologists and soil scientists now believe that soil nutrient stocks decline during swidden cultivation only in soils of low inherent fertility, such as are found in large areas of Africa and the Amazon (Jordan, 1989, pp. 69–92; Lal, 1986, pp. 23–25; Sanchez, 1976, p. 361). The soils of Central America, including those found throughout the southern Maya lowlands (Sanders, 1973, pp. 336–339), have reasonably good fertility characteristics (Jordan, 1989, p. 69), and on these soils agriculture has little immediate discernible impact on soil nutrient retention (Jordan, 1989, p. 69; Lambert and Arnason, 1986, Fig. 5). In fact, in many tropical swidden plots, including those of the modern Maya, stocks of certain types of soil nutrients in cultivated land are as high as or higher than those in the surrounding forest (Brubacher et al., 1989, p. 165; Jordan, 1989, pp. 83–84; Lambert and Arnason, 1989, pp. 305–307; Nakano and Syahbuddin, 1989, p. 327; Sanchez, 1976, p. 377), even

¹⁵ Most but not all areas of the southern lowlands experienced the collapse (Demarest, 2001). One important exception was coastal and northern Belize (Chase and Chase, 1980, 1985; Masson, 1999; Sabloff and Andrews, 1986; see review in Johnston et al., 2001, pp. 151–154).

after several years of cultivation (Uhl, 1987, p. 397). Even at the time of abandonment, the nutrient stocks of fields may be several times that needed for another crop (Jordan, 1985, 1989, p. 84).

This is precisely the opposite of what the conventional model of tropical ecology and the traditional explanation of the Maya collapse predict. That a healthy stock of nutrients must remain in the soils of cultivated fields can be deduced from the fact that after those fields are abandoned they reforest rapidly (Sanchez, 1976, pp. 353–354). If, as the traditional collapse explanation proposes, soil nutrient stocks were significantly depleted by agriculture, rapid post-abandonment reforestation would not occur. Crop yield declines after the second year of cultivation, as previously argued, cannot be attributed in most cases to soil nutrient losses (Brubacher et al., 1989, pp. 165–170; Jordan, 1989; Lal, 1986, pp. 23–24; Lambert and Arnason, 1986, p. 309). What mechanism, then, causes crop yields to decline with each successive year of cultivation in tropical swidden agriculture?

Cultivation lengthening: Soil ecology, weeding, and agriculture

During the last several decades, the model of tropical ecology that serves as a conceptual foundation for archaeologists' traditional explanation of the Maya collapse has been substantially revised. Soils scientists, tropical ecologists, and agronomists have concluded that soil nutrient stocks change during cultivation but not in the manner predicted by a former generation of ecologists (Cassel and Lal, 1992) or by many Mayanists. Phosphorus is a key element in plant growth. One advantage of burning is that it releases from the felled vegetation calcium and magnesium, which raises soil pH, thereby transforming the phosphorus in soils from a bound to a soluble state available to cultigens (Jordan, 1985). Proponents of the new model of the ecological dynamics of tropical swidden agriculture conclude that what declines during cultivation is not the overall amount of soil nutrients but the availability of certain key nutrients to cultigens, including phosphorus (Jordan, 1989, pp. 84–99; Lambert and Arnason, 1989, pp. 304–307; Sanchez, 1976, pp. 372–373). For reasons that are not fully understood, phosphorous undergoes during swidden agriculture a transformation from soluble to insoluble forms (Jordan, 1989). After the second year of cultivation, phosphorus remains in field soils (Nye and Greenland, 1960, p. 117) but in forms that appear to be available to weeds rather than cultigens (Arnason et al., 1982; Brubacher et al., 1989, p. 168; Jordan, 1989, p. 90). This reduction in the availability of phosphorus and other key elements coincides with the destruction of the humus layer and surface organic matter that occurs during the burning phase of slash-and-burn field preparation.

Soil humus and surface organic matter play important roles in tropical agriculture. Humus improves cation exchange, mineralizes to provide key minerals (e.g., phosphorus and nitrogen) required for crop growth, and is carbon-rich (Ahn, 1970, p. 238; Nye and Greenland, 1960, p. 46). The rate of humus mineralization varies with the amount of organic matter in the soil: as organic matter increases, so does the rate of humus mineralization and the availability of phosphorus and nitrogen (Ahn, 1970, pp. 240–241; Ewel, 1986, pp. 250–253). So important is the role of humus in field productivity that some ecologists propose that the decline in nutrient availability and thus crop yields under slash-and-burn agriculture can be attributed largely to humus reduction (Ahn, 1970, p. 244). Conversely, humus restoration may be one of the primary functions of fallowing (Ahn, 1970, pp. 240–241; Nye and Greenland, 1960, pp. 46–47, 64, 107). While it is true that burning felled vegetation enriches soils with high initial nutrient inputs, by destroying vegetation that otherwise might decompose slowly, burning eliminates a potentially important long-term source of surface organic matter and thus soil fertilizer (Jordan, 1989, pp. 90–91; cf. Peters and Neuenschwander, 1988, pp. 21, 30). Intensive burning also can destroy the humus layer within which the nutrients needed for crop cultivation are mineralized. Some ecologists conclude that felled, slowly decomposing surface vegetation plays a more important role in the maintenance of soil nutrient availability in fields than the ash provided by burning, much of which dissolves or washes out of fields before it can be taken up by cultigens (Ahn, 1970, p. 242; Jordan, 1989, pp. 90–91; Schusky, 1989, p. 47; Soane, 1998, p. 114). This has important ramifications for cultivation lengthening: in fields cultivated for more than two or three years, it is decomposing slash rather than ash that sustains soil fertility beyond the second year of cultivation (Jordan, 1989, pp. 90–91). Thus, to lengthen the cultivation period farmers must take steps to protect the humus layer and stocks of surface organic matter, for without these the nutrients needed for agriculture will decline rapidly. Among the practices that traditional tropical farmers employ to maintain high levels of soil organic matter is field mulching (Ewel, 1986, pp. 249–250; Thurston, 1997, p. 8).

The transformation of nutrient availability that occurs during slash-and-burn cultivation disadvantages cultigens by giving a significant competitive edge to weeds, some of which accumulate phosphorus at levels almost three times that of average vegetation (Sanchez, 1976, pp. 372–373). Moreover, weeds are adapted to the disturbed nutrient conditions found in burned fields (Jordan, 1989, p. 102; Norman, 1979, p. 115), and they invariably outcompete cultigens unless controlled by weeding. The competitive success of weeds also can be attributed to their rapid growth (more rapid than most cultigens) and their allocation of resources towards

prolific seed production (Brubacher et al., 1989, p. 170; Ewel, 1986, p. 247; Tilman, 1988). In many tropical fields, including those of the modern Maya, after two or three years of cultivation weeds are the dominant species (Brubacher et al., 1989, p. 171).

That weed invasion, not soil nutrient loss, is the principal cause of crop yield declines in much traditional tropical agriculture (see Sanchez, 1976, p. 378), including that practiced by the modern and ancient Maya, is demonstrated by research conducted by John Lambert and J. Thor Arnason in Maya fields at Indian Church, Belize (Arnason et al., 1982; Brubacher et al., 1989; Lambert and Arnason, 1980, 1986; Lambert et al., 1980). By the third year of cultivation, grain yields declined to 25% of first-year levels while weed biomass increased to levels 350% above those of the first year (Lambert and Arnason, 1986)—a dramatic inverse relationship (Fig. 2). At the same time, large quantities of nutrients shifted location from cultigens, where they were available for human consumption, to weeds, where they were not. By the third year of farming, 30–80% of all key nutrients in field vegetation had become immobilized in weeds during the period of cultivation. Lambert and Arnason (1986, Table 1, Fig. 5) conclude that weeds proliferate at the expense of corn ears, the production of which shrinks as weed biomass increases. Cobs and weeds compete for the same nutrient stocks in an environment where weeds have a distinct competitive advantage (Brubacher et al., 1989, p. 165; Lambert and Arnason, 1986, p. 307). Grain crops seem to be particularly susceptible to yield reductions through weed competition (Ramakrishnan, 1992, p. 153).

That the impacts of weed infestation on Maya crop yields can be controlled through weeding was demonstrated half a century ago by Morris Steggerda (1941) in research conducted at Chichén Itzá, Mexico, in the northern Maya lowlands. To assess the impact of

weeding on swidden production, Steggerda compared on a yearly basis the crop yields and soil nutrients stocks of three experimental plots: (1) Plot A, cultivated continuously for six years—but not weeded—after 10 years of fallowing; (2) Plot B, fallowed for five years after one year of cultivation; and (3) Plot C, cropped twice annually and weeded using “the ancient Maya method” for five years in a row. For year after year, key nutrients in the weeded but cultivated plot (Plot C) were considerably more plentiful than in both the plot cultivated but not weeded (Plot A) and the fallowed field (Plot B). Steggerda’s data show that weeding in tropical agriculture preserves soil nutrient stocks. In a second experiment, Steggerda demonstrated that crop production is enhanced by the preservation of soil nutrients through weeding. For ten consecutive years Steggerda cultivated another Maya field, checking annual crop yields and soil nutrient levels (Morley and Brainerd, 1956, p. 135). Again, he detected no appreciable deterioration of soil chemistry over time (Steggerda, 1941, pp. 119–121). For the first four years of cultivation, farmers weeded the field in the modern manner, chopping down weeds with machetes. Crop yields declined steadily, reaching a fourth year low that was approximately 20% of the first year level (Table 3). Beginning the fifth year and continuing through to the tenth, farmers switched to what Morley and Brainerd (1956, p. 138) call “the ancient way” of weeding, wherein weeds are removed by digging them up by the roots. The crop yield immediately jumped to a level greater than first-year yields, and thereafter yields remained high until the eighth year, when they plunged because of a two-year plague of locusts (Morley and Brainerd, 1956, pp. 138–139). Steggerda correctly proposed that through effective weeding the period of average Maya maize cultivation could be lengthened from three years to seven or possibly eight years. But Steggerda could not convincingly explain how weed growth contributes to crop yield declines, and

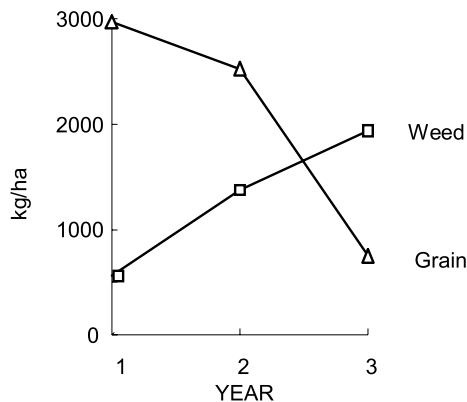


Fig. 2. Grain and weed production measured as kg/ha in a rainy season milpa, Belize (after Lambert and Arnason, 1986, Fig. 3).

Table 3

Steggerda’s corn yields at Chichén Itzá (1933–1940) using “modern” and “ancient” methods of weeding (after Morley and Brainerd, 1956, p. 138)

Year	Yield per acre (lbs.)
<i>Modern weeding method (machete-weeded)</i>	
Year 1	708.4
Year 2	609.4
Year 3	358.6
Year 4	149.6
<i>Ancient weeding method (hand-weeded)</i>	
Year 5	748.0
Year 6	330.0
Year 7	459.8
Year 8	5.5

consequently many archaeologists and agronomists were not persuaded by his proposal.

The implications of the Lambert-Arnason and the Steggerda data are clear: weeding lengthens the period during which a field can be productively cultivated, and it does so by removing weeds that outcompete cultigens by absorbing the nutrients that facilitate cultigen growth. Weeding does not solve the problem of nutrient transformation, but the real significance of nutrient transformation is that it gives weeds a distinct competitive advantage, enabling them to proliferate at the expense of cultigen. Yet for weeding to enhance crop production, it must be properly timed and appropriately carried out (Moody, 1974).

Controlling weed growth in its early stages is essential. Maize, beans, and cotton are severely checked in their early growth stage by even a moderate cover of weeds, and this check can significantly reduce crop yields (Ramakrishnan, 1992, p. 155; Soane, 1998, p. 136; Wrigley, 1982, p. 357). In one study conducted in Africa, maize fields weeded four weeks after planting were 30% more productive than those weeded six weeks after planting (Nye and Greenland, 1960, pp. 80–810). Wrigley (1982, p. 358) reports similar figures for sugar cane: inadequate weed removal during the first six weeks of growth reduced yields by 45%, even when intensive weeding was carried out for the remainder of the growing period. Most critical is the period when primary shoots first appear through the beginning of stalk elongation. Although frequent and persistent weeding always enhances crop yield, if a field is weeded during the early growth stages of the crop, considerable weed growth later may not reduce crop yields (Soane, 1998, p. 136). Conversely, if weeding is delayed, other economic inputs, including fertilizer, may have little positive impact on crop yields (Soane, 1998, p. 137).

Also important is the method of weed removal. Morley (Morley and Brainerd, 1956, pp. 138–139) and others who have studied Maya agricultural practices (Ewell and Merrill-Sands, 1987, p. 103; Nations and Nigh, 1980, p. 14) distinguish between the “modern” method of weeding and the “ancient” or traditional one. The modern method involves weeding a field infrequently—perhaps once or twice a season—which allows weeds to go to seed. It is carried out by cutting weeds at or above ground level with a machete or knife, which leaves the roots intact and scatters the seeds. Farmers who weed using this method cannot control weed growth, and thus beyond the second year of cultivation their crop yields decline (Nations and Nigh, 1980, p. 12). In contrast, practitioners of the traditional method remove weeds as they sprout, especially early in the crop-growing period, so few weeds go to seed. Moreover, they employ a hoe or machete to dig up weeds, which removes or destroys their roots. Using the traditional method, weeds are removed before they have the chance

to deplete a field’s nutrient stocks. Although highly labor-intensive, this method enables farmers to control weed growth for multiple successive cultivation seasons.

The advantages of the traditional weeding method are evident among the modern Maya. Lacandon Maya use the traditional method to cultivate fields for four to five consecutive years, or for as long as weeds can be profitably controlled, after which they abandon fields because the costs of weeding become too great (Nations and Nigh, 1980, pp. 8, 14). In contrast, Lacandon who weed using the modern method must abandon their fields after only one or two years of cultivation. Based on their analyses of Steggerda’s data, Morley and Brainerd (1956, p. 139) estimate that using the traditional method of weeding, ancient Maya farmers could have prolonged the productivity of the average field to perhaps seven or eight years, doubling or tripling beyond the modern average the amount of time that a field could be used before it had to be fallowed.

Consider the following examples. The modern Maya farmers studied by Cowgill (1961), Nations and Nigh (1980), Ewell and Merrill-Sands (1987), Atran (1993) and others cultivate a field an average of two years and fallow for eight, a long-term crop-to-fallow ratio of 2:8. (Note that among modern Maya farmers the crop-to-fallow ratio ranges from 2:8 to 2:20, with an average of 2:12 (Atran, 1993, p. 681; Cowgill, 1962, p. 76; Ewell and Merrill-Sands, 1987, p. 109; Nations and Nigh, 1980, p. 8; Sanders, 1973, p. 347)). Under this regime, a Maya farmer would cultivate each field for 20 years and fallow it for 80 during any given 100-year period. If the same farmer lengthened the period of cultivation to six years an increase comfortably permitted by the traditional weeding method—and maintained the fallow period at eight years, then for every period of 100 years, the field could be cultivated for 43 years and fallowed for 57, a doubling of long-term productivity. If the period of cultivation were increased to eight years—perhaps the outer limits of that allowed by traditional weeding—and the 8-year fallow period maintained, then for every period of 100 years, a field could be cultivated for 50 years and fallowed for 50, a long-term crop-to-fallow ratio of 1:1. Simply by lengthening the period of cultivation through effective weeding, farmers over the course of a century or so could hypothetically increase carrying capacity (but not *per annum* field productivity) by as much as 400%. Even if under intensification the length of the fallow period was increased simultaneously to 10 or even 15 years, as long as the period of cultivation was increased the long-term productivity of the field would dramatically increase, too. For example, by cultivating each field for eight years and fallowing each for 12, the farmer would increase per field productivity and lengthen the fallow period by about 60% above levels characteristic of the 2:8 crop-to-fallow ratio. By lengthening the fallow period, the farmer increases the

agricultural system's ecological stability and thus the long-term productive potential of each field. To engage in cultivation lengthening, however, tropical farmers must engage in one additional important practice: they must mulch their fields with pulled weeds and other vegetative material.

Cultivation lengthening also can result in a significant spatial concentration of production. Because of the increased labor requirements of production per unit of land, under cultivation lengthening each farmer can cultivate considerably fewer plots of land than under extensive bush fallow cultivation. However, this does not necessarily adversely affect per family crop production. Indeed, because under cultivation lengthening per field cropping frequency increases and per field productivity remains high during the period of continuous annual or semi-annual cultivation (see below), per unit farm crop production will (up to a point) remain stable even as individual farm size decreases. The advantages of this outcome to growing farming populations are easily envisioned. Under a 2:20 crop-to-fallow ratio, each farmer needs at least 10 plots if he or she is always to have one under cultivation. Under a 2:12 crop-to-fallow ratio, the minimum number of plots needed decreases to 7; under a 2:8 ratio it decreases to 5. In contrast, under a 6:12 crop-to-fallow ratio easily achievable under cultivation lengthening each farmer needs only three plots to always have one under cultivation; under 8:8 and 6:6 ratios, the minimum number of plots needed decreases to 2 (although 3 presumably is preferable). By switching from extensive bush fallow cultivation to intensive bush fallow cultivation, farmers create on the landscape "Boserupian spaces" (Lee, 1986a) into which populations can grow.

Intensive weeding and weed mulching

Modern research demonstrates that farmers can greatly limit the effect of soil nutrient loss (due to crop harvesting) on productivity by returning nutrients to fields in the form of mulches and manures (Lal, 1975, 1979a,b, 1987; Sanchez, 1976; Thurston, 1997). Especially important as a nutrient-rich mulching material is the plants pulled from the field during weeding (Lal, 1977; Thurston, 1997, pp. 21–22). Weeds are nutrient traps (Lambert and Arnason, 1986, p. 304), and their recycling through mulching plays an important role in field management. When weeds decompose they return nutrients to the soil in soluble forms (Ahn, 1970, pp. 258–259; Juo and Kang, 1989, p. 291; Ramakrishnan, 1992, p. 157; Webster and Wilson, 1980, p. 294; Wrigley, 1982, p. 91).

As farmers periodically mulch their fields during the growing season with nutrient-rich pulled weeds, they replenish the surface supply of organic matter with slowly decomposing plant debris (Thurston, 1997, pp.

25–27). The practice of adding undecomposed plant material to the soil increases the supply of organic carbon, nitrogen, exchangeable potassium, and available phosphorus (Ahn, 1970, p. 258; Wrigley, 1982, p. 91). Thus, weeds absorb insoluble forms of nutrients that cultigens cannot absorb as efficiently; as mulched weeds decompose, those nutrients are returned to the soil in soluble forms that cultigens can absorb. Ahn (1970, p. 258) and Ewel (1986, p. 33) characterize the practice as a type of "short-term artificial fallow." Okigbo and Lal (1982) describe mulching as a viable substitute for bush fallow rotation. Through weed mulching farmers can manage and maintain the fertility of cultivated soils for prolonged periods.

Weed mulching enhances crop production for several other reasons. Mulches reduce soil surface temperature, which lowers soil moisture evaporation and evapotranspiration, which in turn improves germination, the establishment of crop seedlings, and root growth during the early stages of crop growth (Lal, 1979c, p. 319; Soane, 1998, p. 123; Thurston, 1992, p. 88; 1997, p. 26; Wrigley, 1982, p. 94). Further, the presence of fine-root systems reduces topsoil nutrient losses (Berish and Ewel, 1988, p. 73). That is, by enhancing the concentration of roots in the topsoil (Soane, 1998, p. 124) mulching enhances crop production by reducing nutrient losses during cultivation. Also, spreading pulled weed mulches on fields slows later weed growth because it lowers surface light intensity (Soane, 1998, p. 123; Thurston, 1992, p. 88)—weeds are adapted to high light intensity conditions. By slowing the rate at which grasses invade fields after each weeding, weed mulching lowers annual per field weeding costs (Soane, 1998, p. 123; Thurston, 1997, pp. 25–27). By lowering surface light, mulching also reduces the soil surface temperature, which has a similar economic benefit: soil fauna, especially earthworms, build up rapidly, and this improves infiltration and reduces runoff and soil loss, which reduces the farmers' annual hoeing costs (Soane, 1998, p. 123; Thurston, 1997, p. 26). Last, weed mulching is a sustainable means of managing and renewing soil nutrient supplies because it relies on a highly renewable resource—weeds that naturally colonize cultivated fields (Rosemeyer et al., 1999, p. 139). Finally, mulching reduces some plant pathogens, and thus it decreases crop losses in the field, particularly when farmers work the mulch into the soil with hoes (Thurston, 1992, pp. 88–89; 1997, pp. 26, 147–158).¹⁶

The timing of the application of weed mulches has an important impact on crop yields. Mulches have the greatest effect on crop production when applied at the start of the rainy season, during the earliest stages of crop growth (Soane, 1998, pp. 123, 137; Webster and

¹⁶ Thurston (1992, pp. 86–98; 1997, pp. 25–27) lists several additional benefits of field mulching.

Wilson, 1980, p. 294; Wrigley, 1982, p. 93). This is the same season during which aggressive field weeding has comparably beneficial impacts on crop production. By combining weeding and weed mulching early in the growing season, farmers significantly enhance crop yields.

Weed mulching can dramatically enhance crop production (Juo and Kang, 1989, p. 292; Lal, 1975, 1979c, 1987, p. 657; Thurston, 1992, p. 87). Yield responses to grass, forest, and crop residue mulch can be as high as or higher than those obtained from the application of manures and inorganic fertilizers (Lal, 1986, pp. 75–78; 1987, p. 665; Sanchez, 1976, pp. 400–401). In many cases crop yields have been found to increase approximately linearly with increases in mulch application rate (Lal, 1991). Lal (1974a), for example, reports that in experimental plots in the Nigerian rainforest, maize grain yield in mulched plots was approximately 50% higher than in non-mulched plots, irrespective of mulching material. To enjoy this production improvement Nigerian farmers needed to cover cultivated ground with only 1 cm of mulch (Lal, 1974a). Simply by applying crop residues as mulch farmers significantly increased maize yields during five-year cultivation periods (Juo and Kang, 1989, pp. 291–292). Also in Nigeria, dead grass applied as mulch (2.5–3.7 ton/ha) increased sorghum production by approximately 45% (Wrigley, 1982, Table 1.26). Comparable quantities of mulch are available in Maya fields. In Belize, fields cropped two or even three times produce between 2 and 3 tons of mulch of weeds and stover (the stalks, leaves, and other parts of crop plants not removed from fields for food) per hectare per cropping period (Lambert and Arnason, 1980, p. 423; 1986, pp. 308–309; 1989, pp. 304, 311). Also in these fields, the mulch of pulled weeds and crop stover placed by farmers on fields provided cultivated soils with more nutrients than were lost through the removal of crops (Lambert and Arnason, 1989, p. 304). Not surprisingly, the use of weeds and other field vegetation as mulch is widespread among traditional farmers in Africa (Jaiyebo and Moore, 1964, p. 138; Juo and Kang, 1989, p. 289; Netting, 1968, p. 63; Sanchez, 1976, pp. 348–349; Schusky, 1989, p. 47; Thurston, 1997, pp. 73–78), South Asia (Ramakrishnan, 1989, p. 342; 1992, p. 152; Wrigley, 1982, p. 358), New Guinea (Sillitoe, 1996; Wadell, 1972, pp. 159–160), the Pacific islands (Leach, 1999, pp. 313, 316; Thurston, 1992, p. 91; 1997, pp. 82–85), and both Central and South America (Thurston, 1997, pp. 21–22, 31–72).

That Maya farmers recognize the utility of weed mulching is revealed by Cowgill (1961, p. 24) observation that many leave on the ground to decay the grasses removed from fields during weeding. Likewise, Nations and Nigh (1980, p. 9) report that Lacandon farmers collect into piles during the planting season plant debris and extracted weeds, which along with dried corn stalks

they burn during the dry season. Huastec Maya farmers, too, mulch maize plants with slashed weeds (Alcorn, 1990, p. 145). That southern and northern lowland Maya of eastern Mexico all mulch fields with weeds suggests that this widespread practice may have considerable antiquity among the Maya.¹⁷

Cultivation lengthening and erosion control

In addition to controlling soil nutrient loss, weed mulching prevents erosion (Nill and Nill, 1993; Soane, 1998, p. 123; Thurston, 1992, p. 88; Wrigley, 1982, p. 93), which the traditional collapse explanation identifies as a major precipitating factor in the Maya collapse. When tropical soils are deforested and cultivated, their physical properties rapidly degrade, primarily because of the heavy impact of raindrops (Greenland, 1977a, p. 3; 1977b, p. 22; Hudson, 1971; Lal, 1975, 2000, pp. 194–195). Raindrops close surface pores (Lal, 1979a, p. 3)—the channels between soil particles created by the burrowing activity of earthworms and other soil fauna (Lal, 1987, pp. 311–313); macro/biopores govern the ability of soils to accept rainfall (Lal, 1979b, p. 10). Soils with poor porosity develop crusted surfaces that cannot rapidly absorb water, and when rain falls on these surfaces, flow velocity and volume increase, causing erosion

¹⁷ An experimental study conducted by Lambert and Arnason (1989) in Belize seems at first glance to nullify the hypothesis that Maya farmers could have lengthened the cultivation period (sustained yields for more than two sequential years) through intensive mulching. In three plots cultivated twice a year for two years, Lambert and Arnason did the following at the start of the second year. In the first plot they slashed and burned all crop stover, weeds, and other successional plants, which had been left in the field at the end of the first year. In the second plot, they felled and removed that same vegetation community prior to planting. In the third plot, they cut all stover, weeds, and successional species and left them in the field as mulch. To their surprise, the first plot, prepared using slash-and-burn methods, produced considerably greater crop yields than the third, mulched plot. From these results, Lambert and Arnason (1989, p. 312) conclude that mulching fields with crop and weed residues can have “a disastrous effect on crop yield.” However, given that Lambert and Arnason failed to include in their field preparations an important component of traditional slash/mulch agricultural practice, their conclusion should be regarded with skepticism. To lengthen the cultivation period farmers must mulch *and* weed. Lambert and Arnason only did the former: before planting they mulched the plot with weeds and stover; after planting they did not weed it. As Lambert and Arnason (1989, p. 312) acknowledge, the herbaceous weeds allowed to proliferate in the third plot may have suppressed corn production through competition. Intensive weeding and intensive mulching in combination are the key elements of cultivation lengthening. Neither practice alone facilitates cultivation lengthening.

(Gardner, 1977; Hudson, 1971). Erosion, in turn, produces transformations in soil structure associated with lower rates of water absorption, increased runoff, and an additional soil loss (Greenland, 1977b, p. 17). As the experience of the ancient Copan Maya demonstrates (Sanders and Webster, 1994), the impact of erosion on crop production can be devastating. In the Nigerian agricultural fields examined by Lal et al. (1975), for instance, the erosion of a mere 2.5 cm of soil caused a 50% corn yield reduction, while the loss of 7.5 cm resulted in a 90% reduction. Wingard (1992, 1996) has commented at length on the cultural consequences of agriculturally induced erosion caused by the Classic Maya.

By decreasing the velocity with which raindrops strike the soil, mulching protects soil porosity and infiltration, which in turn decreases surface runoff rate and velocity, which prevents erosion (Lal, 1987, pp. 650–652; Marten and Saltman, 1986, p. 48). On slopes with a steepness range of 1–15%, soil and water loss due to erosion can be kept to a minimum through mulching (Lal, 1977, pp. 94–96). Even under conditions of highly intensive cultivation, erosion on gentle slopes will not be a problem so long as soils are properly mulched (Lal, 1974b, p. 54). On steep slopes, farmers can control erosion through a combination of mulching, retaining some live weeds (Moody, 1974, p. 158), and terracing. To receive the maximum benefit, mulches should be applied to fields at the beginning of the growing season (Soane, 1998, p. 123), when the removal of weeds for mulching simultaneously enhances crop yields (Soane, 1998, pp. 123, 137; Wrigley, 1982, p. 93).

The impact of mulching on erosion rates can be dramatic. In Jalisco, Mexico, mulch placed on experimental maize fields reduced erosion by 90% and it simultaneously increased crop productivity by 30% (Maass et al., 1998). The benefit to farmers increases exponentially with increases in the mulch rate. Among the most effective mulches for slope erosion control are weeds and crop residues (Lal, 1977, p. 95; 1979b, p. 12). By providing a protective cover, mulching reduces surface temperature and stabilizes soil moisture regimes, evapotranspiration rates, and soil texture, all of which greatly enhance seedling development and crop growth (Cassel and Lal, 1992; Lal, 1974a, 1975, 1979c, 2000; Soane, 1998, p. 123; Webster and Wilson, 1980, p. 294). Moreover, mulching encourages earthworms, whose movements aerate the soil through the creation of pores and mix surface organic matter and nutrients into the subsoil. Mulching, in fact, can be a more effective method of erosion control than terracing, which slows but does not prevent erosion, as mulching can (Thurston, 1997, pp. 65–159). Thurston, who has extensively reviewed comparative data on indigenous mulching practices in Central and South America (1997, pp. 31–72), proposes that the use of mulches may well be “the most effective strategy for reducing soil erosion on

slopes” (1997, p. 17). Under mulched systems, he concludes, erosion on hillside fields can be reduced to levels equivalent to that characteristic of flat fields (Rosemeyer et al., 1999, p. 144).

Supplementary and related practices

Cultivation lengthening through weeding and weed mulching is a highly labor-intensive variant of a geographically widespread set of traditional agricultural practices now described by agronomists and ecologists as “slash/mulch” agriculture (Rosemeyer et al., 1999; Thurston, 1992, 1994, 1997). Most of the modern worlds’ slash/mulch systems are in use by low to moderate density populations, and so in most cases they are production systems considerably less labor-intensive than the intensive bush fallow cultivation system proposed to have been practiced by the Classic Maya. As defined by Thurston (1997, p. 1), “slash/mulch agricultural systems are characterized by the slashing or cutting of vegetation in situ to produce a mulch for an agricultural crop rather than discarding or burning it as is often the case in traditional shifting cultivation systems.” Slash/mulch agriculture can stand alone as a food-production practice or it can be combined with slash-and-burn agriculture (Thurston, 1997, p. 15). In some cases farmers carry out slash/mulch agriculture in a field immediately after it has been cultivated using the slash-and-burn technique. In other cases, slash/mulch production supplements slash-and-burn production: farmers simultaneously cultivate some fields using the slash/mulch technique and others using the slash-and-burn technique. Some farmers burn the vegetation that has been slashed to produce a mulch (Thurston, 1997, pp. 87–98); most allow it to decompose slowly (Thurston, 1997, p. 15). Farmers can spread slashed materials on the soil surface or incorporate them into the soil through hoeing (Thurston, 1997, p. 19). Throughout the tropical regions of both the New and the Old Worlds, farmers have been practicing slash/mulch agriculture for many centuries (Thurston, 1997, pp. 17, 31–32, 104).

Slash/mulch farmers typically fertilize fields with three general types of mulching material: (1) weeds and stover, both of which are developed in situ in cultivated fields; (2) fresh and dried materials brought to fields from other locations; and (3) green manures, or plants that farmers grow in cultivated fields for the purpose of slashing to produce a mulch. Cultivation lengthening through intensive bush fallow cultivation relies primarily on the first type of mulching practice, although in antiquity the second and third types probably supported it to some degree. Among the materials carried into fields as part of the second type of mulching are night soil and animal manure (including guano and fish remains (Thurston, 1992, pp. 99–100)), household ash (Netting,

1968, p. 63), mud and fertile soil (Schusky, 1989, p. 47), and plant materials, including pruned tree limbs, gathered from nearby forest and fallow vegetation stands. Among the most important mulches of the third type are legume green manures, or slashed leguminous crop covers. Classic Maya intensive bush fallow cultivators probably managed field fertility through some combination of these practices.

What is the significance of the relative flexibility of the fallow period under cultivation lengthening? Fields fallowed for six to eight years reforest with high bush, while those rested for 12–15 years return to low forest. When farmers cultivate for eight years and fallow for 10–15 years, near or immediately adjacent to each cultivated field is a stand of densely limbed trees. Limbs that have been cut from pollarded, pruned, or coppiced trees are one of the most commonly mulched materials in traditional tropical agriculture (Juo and Kang, 1989, p. 290; Ramakrishnan, 1989, p. 338; Schusky, 1989, p. 47; Thurston, 1997, pp. 75, 91, 127–143; Wilken, 1977, pp. 293–296). Typically, farmers gather cut limbs and surface debris, including leaves, in the forest and spread that material across field surfaces during the early stages of the growing season (see Wilken, 1987, for a description of this practice among highland Maya groups). Allowed to decompose slowly, this debris creates in fields soil surface conditions that mimic those of the forest with regard to soil temperature, soil moisture, and soil structural attributes (Wilken, 1977, p. 29). That is, the debris decreases surface light intensity and temperature (which encourages seedling growth while discouraging weed growth), protects soil surfaces from rain-induced erosion, protects and enhances soil surface organic matter and root systems (which increases soil nutrient content), and, through decomposition, supplies soils with a steady stream of key nutrients. Mulching fields with tree limbs and forest debris is a widespread practice among modern tropical farmers in Southeast Asia (Schusky, 1989, p. 56), South Asia (Ramakrishnan, 1989, p. 338), Africa (Juo and Kang, 1989, pp. 290, 297; Thurston, 1992, p. 75), and (in Central America) in Costa Rica (Thurston, 1992, p. 91) and Mayan communities in Guatemala (Wilken, 1977, p. 293; 1987, pp. 54–66).

A variant of this practice is the “cut and carry” method of fallow management, wherein “fallow species are grown on land unsuitable for arable croppings and the prunings are transported to the cultivated plots” (Weischet and Caviedes, 1993, p. 267). Based on his analysis of a soil survey of Guatemala conducted by Simmons et al. (1959), Sanders (1973, p. 342) proposes that only 40% of land in the southern Maya lowlands was suitable for agriculture. The remaining, uncultivated land was forested with vegetation that could have been harvested for mulching materials. Even if land uncultivable for agriculture constituted only 20%

of the southern lowlands, the vegetative material that it supplied could have been used to mulch vast agricultural tracts. A major challenge of the tree limb and forest debris mulching technique is the need to transport large quantities of mulch from outside fields, but this is not a problem where excess labor is available because of high population densities (Thurston, 1992, pp. 97–98). In China, for instance, farmers for centuries transported mulch materials from land unsuitable for agriculture to cultivated land (Thurston, 1992, p. 88). I conclude that because of the opportunities presented under intensive bush fallow cultivation for fallow lengthening (i.e., lengthening the fallow period beyond the 6–10 years characteristic of extensive bush fallow cultivation), mulching of the second type in the southern Maya lowlands would have been an ecologically sustainable and (with regards to labor costs) a feasible practice.

That ancient Maya farmers might have been familiar with mulching of the third type, including leguminous green mulching, is suggested by its widespread practice among modern and colonial-era New World tropical farmers, including contemporary Kekchi Maya farmers, some of whom inhabit areas of the southern Maya lowlands. Early in the cultivation season or prior to its inception, Kekchi farmers in eastern Guatemala plant bean seeds and chop the weeds to cover the seeds with mulch (Carter, 1969). As beans grow through the decomposing mulch they cover it, which limits further weed growth and prevents weeds from competing with cultigens for light, nutrients, or moisture. When after six months the bean plants reach a height of 2.5 m, farmers slash them to the ground, chop the nitrogen-rich, nitrogen-fixing plants finely, and plant maize beneath the bean-plant mulch. Carter (1969, p. 118) claims that plots mulched with bean plants can be cropped for 14 consecutive years without substantial declines in soil fertility. Leguminous green mulching of this type facilitates cultivation lengthening.

Wilk (1985, 1991) describes a closely related Kekchi mulching practice. In southern Belize, farmers cultivate seasonally flooded riverbanks by slashing secondary vegetation at the roots, chopping it up, and dibbling beneath the mat of felled vegetative matter maize seeds. With moderate weeding fields cultivated in this manner produce reasonable yields (Thurston, 1997, p. 43). On average these slashed and mulched fields are cultivated for 5 years and fallowed for three. One field reportedly had been in use continuously for 12 years (Thurston, 1997, p. 43). Cultivation lengthening on floodplain soils undoubtedly is enhanced by their annual re-fertilization through flooding.

Other Maya farmers mulch with woody leguminous species. In the Guatemalan highlands, Maya farmers grow in fields also cultivated with maize a woody leguminous species (*Lathyrus nigrivalvis*) that produces as

much as 100 tons of green matter per hectare (Flores, 1994). In a study by a Guatemalan researcher, the foliage of this plant was cut up and dug it into the ground in plots that had not received any chemical fertilizer application. The corn yield of plots mulched in this manner was 97% higher than that of non-mulched plots.

The mulching of cultivated fields with pulled weeds, felled tree limbs, leguminous green manures, and other materials is such a geographically widespread traditional agricultural practice in the American tropics (see Thurston, 1997) that one suspects that it must have considerable antiquity. Colonial-era Spaniards reported practices identified by Thurston (1997) as slash/mulch agriculture throughout Central and South America, and the practice undoubtedly has long been an important component of Mesoamerican agriculture.¹⁸

Combining intensive weeding and weed mulching with other mulching practices (e.g., weed mulching, green manuring, and cut and carry mulching) would have been decidedly advantageous to the Maya for two reasons. First, intensive bush fallow cultivation produces greater per hectare crop yields than alternative intensification strategies such as short fallow cultivation (Schusky, 1989, pp. 56–57) and extensive bush fallow cultivation (Sanchez, 1976, p. 386). Supplementing weed mulching with complementary mulching techniques only increases the productivity of intensive bush fallow cultivation. Second, unlike alternative intensification strategies, intensive bush fallow cultivation does not in the short term precipitate profound anthropogenic environmental change (although, as noted below, it may in the long term). Because intensive bush fallow cultivation protects the soil by reducing surface temperature and susceptibility to erosion, protects surface organic matter supplies and surface root mats, improves soil porosity and permeability, and renews at regular intervals (through mulching) soil nutrient supplies, it is a more sustainable intensification practice than most alternatives. Combining weed mulching and other mulching practices would increase the stability (the system's capacity to produce consistent and reliable yields) and the sustainability (the system's capacity to endure when subjected to stress (Thurston, 1992, p. 10)) of intensive bush fallow cultivation, and Classic Maya farmers almost certainly would have been aware this.

¹⁸ Although the Kekchi observed by Carter (1969) mulched with velvet beans (*Mucuna* spp. or *Stizolobium* spp.), which were introduced during the last century from Asia (Buckles, 1995), other modern Maya groups mulch with New World beans, such as the Jack bean (*Canavalia ensiformis*) (Jesus Huz, 1994). Modern practitioners continue to adapt this centuries-old fallow enrichment strategy (Rosemeyer et al., 1999) as new bean varieties become available.

Cultivation lengthening and the Classic Maya

Evaluation of the archaeological data

I have argued that through intensive weeding and mulching the southern lowland Classic Maya could have minimized for many decades or a century or more the impact on crop production of the three principal anthropogenic effects of swidden intensification: soil nutrient loss, weed invasions, and soil erosion. The Maya could have controlled weed invasion through intensive weeding, soil nutrient loss through weeding and weed mulching, and topsoil erosion through mulching. That the Maya had the technology, the environmental resources, and the labor needed for cultivation lengthening is clear. But did they actually employ this practice? Although there is no direct and unambiguous evidence of the practice, indirect evidence suggests that at least some Maya populations adopted it. Specifically, in several regions of the southern lowlands, some populations exceeded the estimated productive capacities of alternative intensification strategies that archaeologists believe the Maya employed.

According to Sanders (1973), Rice (1978, 1993), and others (e.g., Turner, 1989), in response to population growth, Classic Maya farmers shifted from extensive bush fallow cultivation to bush fallow cultivation intensified through fallow reduction and then short fallow cultivation. Yet Sanders (1973, Table 22), Rice (1978, Table 4.8), and Culbert (1988, p. 95) acknowledge that the productive capacity of short fallow cultivation would have been too low to have supported estimated Late Classic-period population densities in several southern lowland rural and urban areas. Grounding their hypothesis in the conventional model of tropical ecology, Sanders and Rice propose that high-density Late Classic Maya populations had to have engaged in short fallow cultivation because under the preceding agricultural “stage”—bush fallow cultivation—the only available intensification procedure was fallow reduction. When the Maya shortened the fallow period, Sanders and Rice surmise, fields converted to grasslands and farmers were obliged to adopt grass-fallow (non-plow based short fallow) cultivation.

There is reason to be skeptical of this hypothesis. Short fallow cultivation is a considerably less productive (and less labor-efficient) intensification strategy than intensive bush fallow cultivation (Schusky, 1989, pp. 56–57). (Moreover, it is only about half as productive as extensive bush fallow and forest fallow cultivation (Sanchez, 1976, p. 386)). Grass is difficult to cut, and so under grass-fallow cultivation farmers often burn but do not slash it immediately before the onset of the rainy season. Yet grass produces comparatively little ash, and much of it washes away from and out of

cultivated soils because of the absence of vegetation canopy (Schusky, 1989, pp. 56–57). To maintain soil fertility during the cropping season grass-fallow farmers must devote considerable time to mulching (a practice also characteristic of its more productive alternative, intensive bush fallow cultivation). Further complicating matters, burning grass destroys the aboveground section of the plant but not the root. Unless the roots unaffected by burning are destroyed by digging them out with hoes—a very labor-intensive activity—they will generate new grasses that immediately compete with cultigens for light, water, and nutrients, thus lowering crop yields (Schusky, 1989, pp. 56–57). Because fields cultivated using the grass-fallow method have poor fertility and productivity, farmers generally cultivate for only one year before fallowing. Given: (a) that intensive bush fallow cultivation is a more productive and labor-efficient system than short fallow cultivation and (b) the alleged propensity of traditional farmers to prefer the most efficient, least costly means of production intensification (Boserup, 1965, p. 41), it is likely that many high-density populations would have opted to intensify production through cultivation lengthening rather than short fallow cultivation.

According to the population growth trends reconstructed by Turner (1990) and Whitmore et al. (1990, p. 35)—the most detailed and reliable currently available—unabated growth continued in many areas of the southern Maya lowlands up to the time of the Late Classic-period collapse. Indeed, during the century immediately prior to the onset of the collapse, population growth rates in the high-density central zone seem to have accelerated rather than declined. This is hardly a trend characteristic of a population experiencing acute resource stress. As historical (Lee, 1986b, 1987, 1994; Livi-Bacci, 1991, 1992; Schofield, 1985) and anthropological (Wood, 1998) demographic research demonstrates, in non-industrial societies lacking centralized food storage and distribution facilities, such as southern lowland Classic Maya society, populations very rarely exceed the food-producing capacities of their agricultural systems (unless that capacity is unexpectedly and precipitously reduced by exogenous factors). When the archaeological record reveals that a population in antiquity exceeded the food-producing capacity of one agricultural system yet for decades or even a century continued to grow, we may reasonably assume that it did so because it had adopted or developed a new, more productive system. That segments of the Maya population grew passed the productive capacity of extensive bush fallow and short fallow cultivation suggests that some farming populations had adopted an intensification procedure more productive than these.

Reconstructed Late Classic Maya population growth trends in many southern lowland areas are not consis-

tent with forest fallow cultivation, any type of extensive bush fallow cultivation, or short fallow cultivation. Except in those few areas where farmers intensified production through raised- and drained-field agriculture, the most productive, ecologically sustainable, and feasible (in terms of labor costs and labor availability) intensification strategy was intensive bush fallow cultivation accomplished through intensive grass and herb weeding, weed mulching, and supplementary mulching. Judging from its geographical ubiquity in the tropical Americas, cultivation lengthening through intensive mulching probably has a long history as a New World indigenous practice. As has often been the case in agricultural history (Boserup, 1965, p. 41), Maya farmers may long have known about the existence of intensification strategies such as cultivation lengthening but did not adopt them until critical population densities were reached, at which point crop yield declines compelled innovation.

Cultivation lengthening and the Maya collapse

Cultivation lengthening would have temporarily alleviated but would not have permanently resolved the resource crisis that developed and gained momentum over large areas of the Late Classic southern Maya lowlands. Intensive bush fallow cultivation apparently can be sustained for many decades, but under conditions of continuing population growth and increasing population density it cannot be sustained indefinitely. Fields intensively weeded and mulched lose soil nutrients over time (Sanchez, 1976, p. 384), although only very slowly (Arnason et al., 1982, pp. 32–34; Brubacher et al., 1989, p. 169), often because of the removal of nutrients through crop harvesting and their volatilization during burning (Bruijnzeel, 1998, Table 2). Even in intensively weeded and mulched fields, the rate of nutrient loss is dramatically lower than in fields where farmers practice short fallow swidden (Lal, 1974b). Under both short fallow and intensive bush fallow cultivation, the key to long-term sustainability is reforestation through fallowing, and the foundation of reforestation is the roots, shoots, and seeds of successional species that survive in fields during cultivation. Any process that compromises field reforestation endangers the future sustainability of production. Under cultivation lengthening, production is sustainable partly because of the marked reduction in or the elimination of slashing and burning, the intense heat of which can burn out and destroy critical root and seed banks (Uhl, 1987, p. 400). Yet as Maya farmers hoed fields to remove weeds by their roots, they must inadvertently have destroyed some portion of the root stocks of fallow species, which would have slowed reforestation and thus the succession process that displaces weeds from fields. Weed infestations may have become progressively more severe, adversely affecting

the land's capacity to reforest and thus its long-term agricultural potential. On slopes, topsoils gradually would have eroded in the manner suggested by lake-core data (Rice, 1993, pp. 29–32).

When populations intensify agricultural production through technological or organizational innovation, they create a “Boserupian space” (Lee, 1986a) into which they can continue to grow, at least until the productive capacity of the new agricultural system is reached (Boserup, 1965; Lee, 1994). Under cultivation lengthening, these Boserupian spaces are created through a spatial concentration of production (see above). Through the continued growth registered in archaeological reconstructions, Late Classic Maya populations eventually would have approached and then surpassed the productive capacity of intensive bush fallow cultivation (characterized by crop-to-fallow ratios that range between 6:6 and 8:15). Lacking plows, draft animals, and opportunities for extensive irrigation, most Maya could not intensify beyond the limits of intensive bush fallow cultivation. At that point, Maya farmers would have had only two opportunities for further intensification. First, they could have intensified mulching by spreading larger quantities of organic material on fields more frequently. But mulching cannot be intensified indefinitely. Eventually the amount of mulched material covering fields will become so great that crop production will be adversely affected, or farmers will reach the limits of or exhaust the supply of mulched organic materials. Second, Maya farmers could have intensified production by progressively shortening the fallow to a period less than the 6–10 years needed for intensive bush fallow cultivation to remain sustainable. However, fallow shortening would have destabilized the agricultural enterprise by triggering in fields the three anthropogenic changes previously identified as the ecological foundations of the southern lowland collapse: progressive weed infestations, soil nutrient stock declines, and topsoil erosion. Presumably farmers experimented with both strategies, but in areas of high population density neither would have provided a viable long-term resolution to the problem of increasing resource stress. As environmental resources degraded, cultivation costs would have increased and per capita food availability would have declined, pushing many dense Maya populations towards a crisis from which they could not escape. Here the traditional explanations of the ecological foundations of the Maya collapse (Abrams and Rue, 1988; Abrams et al., 1996; Culbert, 1988; Rice, 1993; Rice et al., 1985; Sanders, 1973; Sanders and Webster, 1994; Santley et al., 1986; Webster, 2002; Willey and Shimkin, 1973), which cite anthropogenic change, complex demographic processes, and increased competition for resources as precipitating factors, and the amendment proposed here converge.

Conclusions

In summary, this paper develops a model of tropical agricultural intensification through intensive bush fallow cultivation that applies to: (a) traditional cereal crop cultivation in (b) moist-to-wet tropical lowland environments whose soils have good fertility characteristics (i.e., where agriculture has little immediate impact on soil nutrient retention) under (c) conditions of high population density. The model does not apply to tropical environments with nutrient-poor soils or to non-cereal cultivation. Whether the model applies to pre-industrial cultivation outside of Mesoamerica has yet to be determined. I suspect that it has broad geographical applicability under the conditions just specified.

Under these conditions, a primary (but not the only) motivation for cultivation lengthening is increasing pressure on resources (broadly manifested as decreasing per capita food availability). When population density is linked to significant resource stress some farmers find it worthwhile to shift to intensive bush fallow cultivation, which is a highly labor-intensive land-use system. In some tropical agricultural societies lacking plows and draft animals, access to chemical fertilizers or substantial quantities of animal manures, or environmental opportunities for irrigation, a productive and (from the viewpoint of labor availability) viable means of intensifying beyond the limits of extensive bush fallow is cultivation lengthening through intensive bush fallow cultivation.

To lengthen the cultivation period, tropical farmers exploit the dynamics of nutrient recycling in cultivated fields. The key labor processes that sustain the practice are intensive weeding and the mulching of cultivated fields with pulled weeds (primarily herbs and grasses) and other vegetative and non-vegetative material, all of which in landscapes cultivated through intensive bush fallow are abundantly available in and near fields. Farmers will fine-tune and modify the method as necessary to adjust for local climatic (including precipitation) conditions, crop patterns, and soil types.

The model's potential analytical utility becomes evident when it is applied to the problem of demographic, agricultural, and ecological relationships in Classic-period southern lowland Maya society. I propose that prior to the ninth-century collapse, some but not all high-density southern lowland populations included cultivation lengthening in their repertoire of agricultural intensification strategies. Those Maya most likely to have adopted the practice include farmers of the very densely populated southern lowland central zone. Where adopted as an intensification strategy, cultivation lengthening would have been the focal point of a suite of coeval food-production strategies, including kitchen gardening, orcharding, intercropping, the protection and fostering in cultivated fields of economically useful

trees, bushes, and shrubs, the cultivation of *bajo* and river margins, the management of water in fields, and practices such as fishing, hunting, and gathering (Atran, 1993; Cowgill, 1962; Dunning et al., 1998, 1999, 2002; Fedick, 1996; Fedick et al., 2000; Flannery, 1982; Harrison and Turner, 1978; Nations and Nigh, 1980; Pohl, 1990; Rice, 1993; Sanders, 1973; Scarborough, 1993; Turner and Harrison, 1983).¹⁹

Cultivation lengthening through intensive bush fallow cultivation is a labor-intensive variant of a set of practices known as slash/mulch agriculture, which modern, moderately dense populations (including Maya populations) engage in throughout the American tropics (Thurston, 1992, 1994, 1997; Thurston et al., 1994). The practice's geographical ubiquity suggests that it has considerable antiquity in the New World. As resource stress increased during the Late Classic period, Maya farming probably did not undergo a sudden, step-like evolutionary transformation from non-mulch-based agriculture (e.g., extensive bush fallow or short fallow cultivation) to mulch-based cultivation lengthening (contrary to the predictions of Boserup's general model of the evolution of agriculture). Given that slash/mulch practices are an important component of modern agriculture among tropical farming populations of moderate density, it is possible that this was also the case in antiquity. Among the Maya, mulch-based or mulch-aided agriculture in outfields may have been an important component of production long before the Late-Classic era of high population densities. If so, Classic Maya farmers may have intensified agriculture not suddenly but gradually, over the course of a century or so, by weeding and mulching their fields with progressively

greater intensity in response to escalating resource stress. The adoption of intensive bush fallow cultivation may explain how for many decades high-density southern lowland Maya populations sustained themselves agriculturally before during the ninth and tenth centuries AD suffering a precipitous demographic decline.

Acknowledgments

I am deeply grateful to Rattan Lal, Carl Jordan, David Thurston, and Martin Quigley, who critically evaluated the model of cultivation lengthening from soil science, ecological, and agricultural perspectives. I am particularly grateful to Rattan Lal, who generously and patiently answered my many questions about tropical agriculture, ecology, and soils. I also wish to express my sincere thanks to Joy McCorriston, Stephen Houston, Robert Wenke, David Webster, T. Patrick Culbert, and Clark Larsen, who read and commented on (in some cases several) earlier drafts of this paper. Two anonymous reviewers provided perceptive and very helpful comments. Of course, all errors or omissions in fact and interpretation are entirely the author's responsibility.

References cited

¹⁹ This paper is not the first to suggest that Late Classic Maya farmers may have attempted to improve crop yields through intensive field mulching and fertilizing. Culbert (1988, p. 98) proposed that southern lowland Maya could have used mulching and other measures to restore or maintain soil fertility in cultivated fields, but he imagined that the practice would have transpired in the context of extensive bush fallow cultivation intensified through fallow shortening rather than cultivation lengthening accomplished through intensive bush fallow cultivation. Similarly, Sanders (1973, p. 335) concluded that southern lowland soils could not have been "permanently cropped over long periods of time without exotic nutrients," but he doubted that even intensive fertilization would have enabled farmers "to sustain permanent or very short cropping cycles." Sanders, in other words, assumed that intensive fertilization would have been a component of short fallow or annual cultivation systems. Rice (1978, p. 57) proposed that in the context of intensive kitchen gardening and shifting cultivation, "only concerted efforts at organic fertilizing could compensate for harvesting of produce and prevent nutrient depletion," but he, too, assumed that intensive fertilizing would have been a component of intensification through fallow reduction rather than through cultivation lengthening.

- Abrams, E.M., Rue, D.J., 1988. The causes and consequences of deforestation among the prehistoric Maya. *Human Ecology* 16 (4), 377–395.
- Abrams, E.M., Freter, A., Rue, D.J., Wingard, J.D., 1996. The role of deforestation in the collapse of the Late Classic Copan Maya state. In: Sponsel, L., Headland, T., Bailey, R. (Eds.), *Tropical Deforestation: The Human Dimension*. Columbia University Press, New York, pp. 55–75.
- Adams, R.E., 1973. Maya Collapse: transformation and termination in the ceramic sequence at Altar de Sacrificios. In: Culbert, T.P. (Ed.), *The Classic Maya Collapse*. University of New Mexico Press, Albuquerque, pp. 133–164.
- Adams, R.E., 1983. Ancient land use and culture history in the Pasion River region. In: Vogt, E.Z., Leventhal, R.M. (Eds.), *Prehistoric Settlement Patterns: Essays in Honor of Gordon R. Willey*. University of New Mexico Press and Harvard University, Albuquerque and Cambridge, MA, pp. 319–336.
- Adams, R.E., Brown, W.E., Culbert, T.P., 1981. Radar mapping, archaeology, and ancient Maya land use. *Science* 213 (4515), 1457–1463.
- Ahn, P.M., 1970. *West African Soils*. Oxford University Press, New York.
- Alcorn, J.B., 1990. Indigenous agroforestry strategies meeting farmer's needs. In: Anderson, A.B. (Ed.), *Alternatives to Deforestation: Steps Towards Sustainable Use of the Amazon Rain Forest*. Columbia University Press, New York, pp. 141–151.
- Arnason, T., Lambert, J.D.H., Gale, J.L., Cal, J., Vernon, H., 1982. Decline of soil fertility due to intensification of land

- use by shifting agriculturalists in Belize, Central America. *Agro-Ecosystems* 8, 27–37.
- Ashmore, W., 1981. *Lowland Maya Settlement Patterns*. University of New Mexico Press, Albuquerque.
- Athens, J.S., 1999. Reply to Leach. *Current Anthropology* 40 (3), 321–322.
- Atran, S., 1993. Itz'á Maya tropical agro-forestry. *Current Anthropology* 34 (5), 633–699.
- Ball, J.W., Kelsay, R.G., 1992. Prehistoric intrasettlement land use and residual soil phosphate levels in the Upper Belize Valley, Central America. In: Killion, T.W. (Ed.), *Gardens of Prehistory: The Archaeology of Settlement Agriculture in Greater Mesoamerica*. University of Alabama Press, Tuscaloosa, pp. 234–262.
- Beach, T., Dunning, N.P., 1995. Ancient Maya terracing and modern conservation in the Petén rain forest of Guatemala. *Journal of Soil and Water Conservation* 50 (2), 138–145.
- Berish, C.W., Ewel, J.J., 1988. Root development in simple and complex tropical successional ecosystems. *Plant and Soil* 106, 73–84.
- Binford, M.W., Brenner, M., Whitmore, T.J., Higuera-Gundy, A., Deevey, E.S., 1987. Ecosystems, paleoecology, and human disturbance in subtropical and tropical America. *Quaternary Science Reviews* 6, 115–128.
- Boserup, E., 1965. *The Conditions of Agricultural Growth: The Economics of Agrarian Change Under Population Growth*. Aldine, Chicago.
- Boserup, E., 1981. *Population and Technological Change: A Study of Long-Term Trends*. University of Chicago Press, Chicago.
- Boserup, E., 1990. In: Schultz, T.P. (Ed.), *Economic and Demographic Relationships in Development*. Johns Hopkins University Press, Baltimore.
- Bray, F., 1986. *The Rice Economies: Technology and Development in Asia*. Blackwell, New York.
- Brookfield, H.C., 1972. Intensification and disintensification in Pacific agriculture. *Pacific Viewpoint* 13 (1), 30–48.
- Brubacher, D., Arnason, J.T., Lambert, J.D.H., 1989. Woody species and nutrient accumulation during the fallow period of milpa farming in Belize, CA. *Plant and Soil* 114, 165–172.
- Bruijnzeel, S., 1998. Soil chemical changes after tropical disturbance and conversion: the hydrological perspective. In: Schulte, A., Ruhiyat, D. (Eds.), *Soils of Tropical Forest Ecosystems: Characteristics, Ecology, and Management*. Springer, Berlin, pp. 45–61.
- Buckles, D., 1995. Velvetbean: a “new” plant with a history. *Economic Botany* 49 (1), 13–25.
- Carr, R.E., Hazard, J.E., 1961. *Map of the Ruins of Tikal, El Peten, Guatemala*. Tikal Reports 11, University Museum Monograph. University Museum, University of Pennsylvania, Philadelphia.
- Carter, W.E., 1969. *New Lands and Old Traditions: Kekchi Cultivators in the Guatemalan Lowlands*. University of Florida Press, Gainesville.
- Cassel, D.K., Lal, R., 1992. Soil physical properties of the tropics: common beliefs and management restraints. In: Lal, R., Sanchez, P. (Eds.), *Myths and Science of Soils of the Tropics*. Soil Science Society of America Publication No. 29. Soil Science Society of America, Madison, WI, pp. 61–89.
- Chase, A.F., Chase, D.Z., 1980. Yucatec influence in Terminal Classic northern Belize. *American Antiquity* 47, 596–614.
- Chase, A.F., Chase, D.Z., 1985. Postclassic temporal and spatial frames for the Lowland Maya: a background. In: Chase, A.F., Rice, P. (Eds.), *The Lowland Maya Postclassic*. University of Texas Press, Austin, pp. 9–22.
- Chase, A.F., Chase, D.Z., 1996. More than kin and king: Centralized political organization among the Classic Maya. *Current Anthropology* 37 (5), 803–810.
- Chase, A.F., Chase, D.Z., 1998. Scale and intensity in Classic period Maya agriculture: terracing and settlement at the “garden city” of Caracol, Belize. *Culture and Agriculture* 20 (2/3), 60–77.
- Cook, O.F., 1909. *Vegetation Affected by Agriculture in Central America*. Bureau of Plant Industry Bulletin, No. 145. US Department of Agriculture, Washington, DC.
- Cook, O.F., 1921. *Milpa Agriculture, a Primitive Tropical System*. Smithsonian Institution Annual Report, 1919, Pub. 2590. Smithsonian Institution, Washington, DC.
- Cooke, C.W., 1931. Why the Mayan cities of the Peten district, Guatemala, were abandoned. *Journal of the Washington Academy of Sciences* 21 (13), 283–287.
- Cooke, C.W., 1933. A possible solution of a Mayan mystery. *Scientific Monthly* 37, 362–365.
- Cowgill, U., 1961. Soil fertility and the ancient Maya. *Transactions of the Connecticut Academy of Arts and Sciences* 42, 1–56.
- Cowgill, U., 1962. An agricultural study of the southern Maya lowlands. *American Anthropologist* 64, 273–286.
- Culbert, T.P., 1973. *The Classic Maya collapse*. University of New Mexico Press, Albuquerque.
- Culbert, T.P., 1988. The collapse of Classic Maya civilization. In: Yoffee, N., Cowgill, G. (Eds.), *The Collapse of Ancient States and Civilizations*. University of Arizona Press, Tucson, pp. 69–101.
- Culbert, T.P., Kosakowsky, L.J., Fry, R.E., Haviland, W.M., 1990. The population of Tikal, Guatemala. In: Culbert, T.P., Rice, D.S. (Eds.), *Precolumbian Population History in the Maya Lowlands*. University of New Mexico Press, Albuquerque, pp. 103–122.
- Culbert, T.P., Levi, L.J., Cruz, L., 1990. Lowland Maya wetland agriculture: The Río Azul agronomy program. In: Clancy, F.C., Harrison, P.D. (Eds.), *Vision and Revision in Maya Archaeology*. University of New Mexico Press, Albuquerque, pp. 115–124.
- Culbert, P.T., Levi, L., McKee, B., Kunen, J., 1996. Investigaciones arqueológicas en el Bajo la Justa entre Yaxha y Nakum. In: Laporte, J.P., Escobedo, H.L. (Eds.), *IX Simposio de Investigaciones Arqueológicas en Guatemala*. Instituto Nacional de Antropología e Historia, Guatemala City, Guatemala, pp. 51–57.
- Culbert, T.P., Rice, D.S., 1990. *Precolumbian Population History in the Maya Lowlands*. University of New Mexico Press, Albuquerque.
- Curtis, J.H., Brenner, M., Hodell, D.A., Balsler, R.A., Islebe, G.A., Hooghiemstra, H., 1998. A multiproxy study of Holocene environmental change in the Maya lowlands of Petén, Guatemala. *Journal of Paleolimnology* 19, 139–159.
- Danforth, M.E., 1994. Stature change in the prehistoric Maya of the southern lowlands. *Latin American Antiquity* 5, 206–211.
- Danforth, M.E., 1997. Late Classic Maya health patterns: evidence from enamel microdefects. In: Whittington, S.L., Reed, D.M. (Eds.), *Bones of the Maya: Studies of Ancient*

- Skeletons. Smithsonian Institution Press, Washington, DC, pp. 127–137.
- Danforth, M.E., 1999. Coming up short: Stature and nutrition among the ancient Maya of the southern lowlands. In: White, C.D. (Ed.), *Reconstructing Ancient Maya Diet*. University of Utah Press, Salt Lake City, pp. 103–118.
- Deevey Jr., E.S., Rice, D.S., Rice, P.M., Vaughan, H.H., Brenner, M., Flannery, M.S., 1979. Mayan urbanism: impact on a tropical karst environment. *Science* 206 (19), 298–306.
- Demarest, A.A., 1992. Ideology in ancient Maya cultural evolution: the dynamics of galactic polities. In: Demarest, A.A., Conrad, G.W. (Eds.), *Ideology and Pre-Columbian Civilizations*. School of American Research Press, Santa Fe, pp. 135–158.
- Demarest, A.A., 1997. The Vanderbilt Petexbatún Regional Archaeology Project 1989–1994: Overview, history, and major results of a multidisciplinary study of the Classic Maya collapse. *Ancient Mesoamerica* 8(2), 209–228.
- Demarest, A.A., 2001. Climatic change and the Classic Maya collapse: A return to catastrophism. *Latin American Antiquity* 12 (1), 105–107.
- Devevan, W.M., 1971. Campa subsistence in the Gran Pajonal, eastern Peru. *The Geographical Review* 61, 496–518.
- Devevan, W.M., 1982. Hydraulic agriculture in the American tropics: forms, measures, and recent research. In: Flannery, K.V. (Ed.), *Maya Subsistence: Studies in Memory of Dennis Puleston*. Academic Press, New York, pp. 181–204.
- Dumond, D.E., 1961. Swidden agriculture and the rise of Maya civilization. *Southwestern Journal of Anthropology* 17, 332–349.
- Dunning, N.P., Beach, T., 1994. Soil erosion, slope management, and ancient terracing in the Maya lowlands. *Latin American Antiquity* 5 (1), 51–69.
- Dunning, N.P., Beach, T., Farrell, P., Luzzander-Beach, S., 1998. Prehispanic agroecosystems and adaptive regions in the Maya lowlands. *Culture and Agriculture* 20 (2/3), 87–101.
- Dunning, N.P., Beach, T., Rue, D., 1997. The paleoecology and ancient settlement of the Petexbatún region, Guatemala. *Ancient Mesoamerica* 8 (2), 255–266.
- Dunning, N.P., Luzzander-Beach, S., Beach, T., Jones, J.G., Scarborough, V., Culbert, T.P., 2002. Arising from the *bajos*: the evolution of a neotropical landscape and the rise of Maya civilization. *Annals of the American Association of Geographers* 92 (2), 267–283.
- Dunning, N.P., Scarborough, V., Valdez Jr., F., Luzzander-Beach, S., Beach, T., Jones, J.G., 1999. Temple mountains, sacred lakes, and fertile fields: ancient Maya landscapes in northwestern Belize. *Antiquity* 73 (281), 650–656.
- Emerson, R.A., Kempton, J.H., 1935. Agronomic investigations in Yucatan. *Carnegie Institution of Washington Yearbook* 34, 138–142.
- Ewel, J.J., 1986. Designing agricultural ecosystems for the humid tropics. *Annual Review of Ecology and Systematics* 17, 245–271.
- Ewell, P., Merrill-Sands, D., 1987. Milpa in Yucatan: a long-fallow maize system and its alternatives in the Maya peasant economy. In: Turner II, B.L., Brush, S. (Eds.), *Comparative Farming Systems*. Guilford Press, New York, pp. 95–129.
- Fedick, S.L., 1996. *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*. University of Utah Press, Salt Lake City.
- Fedick, S.L., Ford, A., 1990. The prehistoric agricultural landscape of the central Maya lowlands: an examination of local variability in a regional context. *World Archaeology* 22 (1), 18–33.
- Fedick, S.L., Morrison, B.A., Andersen, B.J., Boucher, S., Acosta, J.C., Mathews, J., 2000. Wetland manipulation in the Yalahau region of the Northern Maya lowlands. *Journal of Field Archaeology* 27 (2), 131–152.
- Fialko, V., Culbert, T.P., in press. Implications of the Tikal and Yaxha bajo communities for understanding the end of the Classic Period in Peten, Guatemala. In: Rice, D.S., Rice, P.M., Demarest, A. (Eds.), *The Terminal Classic in the Maya Lowlands: Collapse, Transition, and Transformation*. Westview Press, Boulder, CO.
- Flannery, K.V., 1982. *Maya Subsistence: Studies in Memory of Dennis E. Puleston*. Academic Press, New York.
- Flores, M., 1994. The use of leguminous crop covers in traditional farming systems in Central America. In: Thurston, H.D., Smith, M., Abawi, G., Kearl, S. (Eds.), *Tapado. Slash/Mulch: How Farmers Use It And What Researchers Know About It*. Cornell Institute for Food, Agriculture, and Development, Ithaca, NY, pp. 149–156.
- Food and Agriculture Organization, 1958. *Efficient Use of Fertilizers*. Food and Agriculture Organization of the United Nations (FAO), Agricultural Studies No. 43. FAO, Rome.
- Ford, A., 1986. *Population Growth and Social Complexity: An Examination of Settlement and Environment in the Central Maya Lowlands*. Anthropological Research Paper No. 35. Arizona State University, Tempe.
- Ford, A., 1990. Maya settlement in the Belize River area: variations in residence patterns of the central Maya lowlands. In: Culbert, T.P., Rice, D.S. (Eds.), *Pre-Columbian Population History in the Maya Lowlands*. University of New Mexico Press, Albuquerque, pp. 167–182.
- Ford, A., 1991. Problems with evaluation of population from settlement data: examination of ancient Maya residential patterns in the Tikal-Yaxha intersite area. *Estudios de Cultura Maya* 18, 156–186.
- Ford, A., Fedick, S., 1992. Prehistoric Maya settlement patterns in the Upper Belize River area: initial results of the Belize River Archaeological Settlement Survey. *Journal of Field Archaeology* 19, 35–49.
- Gardner, W.R., 1977. Water entry and movement in relation to erosion. In: Greenland, D.J., Lal, R. (Eds.), *Soil Conservation and Management in the Humid Tropics*. Wiley, New York, pp. 25–32.
- Glassman, D.M., Garber, J.F., 1999. Land use, diet, and their effects on the biology of the prehistoric Maya of Northern Ambergris Cay, Belize. In: White, C.D. (Ed.), *Reconstructing Ancient Maya Diet*. University of Utah Press, Salt Lake City, pp. 119–132.
- Gliessman, S.R., Turner II, B.L., Rosado May, F.J., Amador, M.F., 1983. Ancient raised field agriculture in the Maya lowlands of southeastern Mexico. In: Darch, J.P. (Eds.), *Drained Field Agriculture in Central and South America*. BAR International Series No. 189. British Archaeological Reports, Oxford, pp. 90–110.

- Gourou, P., 1953. *The Tropical World*. Longman, Green and Co, London.
- Greenland, D.J., 1977a. The magnitude and importance of the problem. In: Greenland, D.J., Lal, R. (Eds.), *Soil Conservation and Management in the Humid Tropics*. Wiley, New York, pp. 3–10.
- Greenland, D.J., 1977b. Soil structure and erosion hazard. In: Greenland, D.J., Lal, R. (Eds.), *Soil Conservation and Management in the Humid Tropics*. Wiley, New York, pp. 17–24.
- Hammond, N., Ashmore, W., 1981. Lowland Maya settlement: geographical and chronological frameworks. In: Ashmore, W. (Ed.), *Lowland Maya Settlement Patterns*. University of New Mexico Press, Albuquerque, pp. 19–36.
- Hansen, R.D., 2000. The first cities the beginnings of urbanization and state formation in the Maya lowlands. In: Grube, N. (Ed.), *Maya: Divine Kings of the Rainforest*, Konemann, Cologne, pp. 50–68.
- Harris, D.R., 1971. The ecology of swidden cultivation in the upper Orinoco rain forest, Venezuela. *The Geographical Review* 61, 475–495.
- Harrison, P.D., 1978. Bajos revisited: visual evidence for one system of agriculture. In: Harrison, P.D., Turner II, B.L. (Eds.), *Prehispanic Maya Agriculture*. University of New Mexico Press, Albuquerque, pp. 247–254.
- Harrison, P.D., 1982. Subsistence and society in eastern Yucatan. In: Flannery, K.V. (Ed.), *Maya Subsistence: Studies in Memory of Dennis E. Puleston*. Academic Press, New York, pp. 119–130.
- Harrison, P.D., 1993. Aspects of water management in the southern Maya lowlands. In: Scarborough, V., Isaac, B. (Eds.), *Economic Aspects of Water Management in the Prehispanic New World*. Research in Economic Anthropology Supplement 7. JAJ Press, Greenwich, CT, pp. 71–122.
- Harrison, P.D., Turner II, B.L., 1978. *Prehispanic Maya Agriculture*. University of New Mexico Press, Albuquerque.
- Haviland, W.A., 1965. Prehistoric settlement at Tikal, Guatemala. *Expedition* 7 (3), 14–23.
- Haviland, W.A., 1967. Stature at Tikal, Guatemala: implications for ancient Maya demography and social organization. *American Antiquity* 32, 429–433.
- Haviland, W.A., 1970. Tikal, Guatemala and Mesoamerican urbanism. *World Archaeology* 2 (2), 186–198.
- Haviland, W.A., 1972. Family size, prehistoric population estimates and the Ancient Maya. *American Antiquity* 37, 135–139.
- Healy, P.F., Lambert, J.H., Arnason, J.T., Hebda, R., 1983. Caracol, Belize: evidence of ancient Maya agricultural terraces. *Journal of Field Archaeology* 10, 397–410.
- Hester Jr., J.A., 1952. Agriculture, economy, and population densities of the Maya. *Carnegie Institution of Washington Yearbook* 1952 51, 266–271.
- Hester Jr., J.A., 1953a. Agriculture, economy, and population densities of the Maya. *Carnegie Institution of Washington Yearbook* 1953 52, 288–292.
- Hester Jr., J.A., 1953b. Maya agriculture. *Carnegie Institution of Washington Yearbook* 1953 52, 297–298.
- Houston, S.D., 1993. *Hieroglyphs and History at Dos Pilas: Dynastic Politics of the Classic Maya*. University of Texas Press, Austin.
- Hudson, N., 1971. *Soil Conservation*. B.T. Batsford, London.
- Hunt, R.C., 2000. Labor productivity and agricultural development: Boserup revisited. *Human Ecology* 28 (2), 251–277.
- Inomata, T., 1997. The last day of a fortified Classic Maya center: archaeological investigations at Aguateca, Guatemala. *Ancient Mesoamerica* 8 (2), 337–352.
- Islebe, G.A., Hooghiemstra, H., Brenner, M., Curtis, J.H., Hodell, D.A., 1996. A Holocene vegetation history from lowland Guatemala. *The Holocene* 6 (3), 265–271.
- Jaiyebo, E.O., Moore, A.W., 1964. Soil fertility and nutrient storage in different soil and vegetation systems in a tropical rainforest environment. *Tropical Agriculture* 41 (2), 129–140.
- Jarosz, L., 1993. Defining and explaining tropical deforestation: shifting cultivation and population growth in colonial Madagascar (1896–1940). *Economic Geography*, 366–379.
- Jesus Huz, M.D., 1994. The use of *Canavalia ensiformis* and other leguminous species as mulches for farming in the Yucatan. In: Thurston, H.D., Smith, M., Abawi, G., Kearn, S. (Eds.), *Tapado. Slash/Mulch: How Farmers Use It And What Researchers Know About It*. Cornell Institute for Food, Agriculture, and Development, Ithaca, NY, pp. 207–208.
- Johnston, K.J., 1994. The invisible” Maya: Late Classic minimally-platformed residential settlement at Itzán, Petén, Guatemala. Ph.D. Dissertation, Yale University. University Microfilms, Ann Arbor.
- Johnston, K.J., 1997. La ecología de la agricultura tropical y el colapso de los Maya Clásicos. In: Laporte, J.P., Escobedo, H. (Eds.), *IX Simposio de Arqueología Guatemalteca*. Museo Nacional de Arqueología e Etnología, Guatemala City, Guatemala, pp. 483–490.
- Johnston, K.J., 2002. Protrusion, bioturbation, and settlement detection during surface survey: the lowland Maya case. *Journal of Archaeological Method and Theory* 9 (1), 1–67.
- Johnston, K.J., Breckenridge, A.J., Hansen, B.C., 2001. Paleoeological evidence of an Early Postclassic occupation in the southwestern Maya lowlands: Laguna Las Pozas, Guatemala. *Latin American Antiquity* 12 (2), 149–166.
- Jordan, C.F., 1985. *Nutrient Cycling in Tropical Forest Ecosystems*. Wiley, Chichester.
- Jordan, C.F., 1989. *An Amazonian Rain Forest: The Structure and Function of a Nutrient-Stressed Ecosystem and the Impact of Slash-and-Burn Agriculture*. UNESCO and The Parthenon Publishing Group, Paris and Park Ridge, NJ.
- Jordan, C.F., Herrera, R., 1981. Tropical rain forests: are nutrients really critical? *American Naturalist* 117, 167–180.
- Juo, A.S., Kang, B.T., 1989. Nutrient effects of modification of shifting cultivation in West Africa. In: Proctor, J. (Ed.), *Mineral Nutrients in Tropical Forest and Savanna Ecosystems*. Blackwell Scientific, Oxford, pp. 289–300.
- Killion, T.W., Sabloff, J.A., Tourtellot, G., Dunning, N.P., 1989. Intensive surface collection of residential clusters at Terminal Classic Sayil, Yucatan, Mexico. *Journal of Field Archaeology* 16, 273–294.
- Kirch, P.V., 1994. *The Wet and the Dry: Irrigation and Agricultural Intensification in Polynesia*. University of Chicago Press, Chicago.
- Kricher, J.C., 1989. *A Neotropical Companion*. Princeton University Press, Princeton.

- Kunen, J.L., Culbert, T.P., Fialko, V., McKee, B., Grazioso, L., 2000. Bajo communities: a case study from the central Petén. *Culture and Agriculture* 22 (3), 15–31.
- Lal, R., 1974a. Soil temperature, soil moisture and maize yield from mulched and unmulched tropical soils. *Plant and Soil* 40, 129–143.
- Lal, R., 1974b. Soil erosion and shifting agriculture. *Shifting Cultivation and Soil Conservation in Africa*. Food and Agriculture Organization of the United Nations, Rome.
- Lal, R., 1975. Role of Mulching Techniques in Tropical Soil and Water Management. International Institute of Tropical Agriculture, Ibadan, Nigeria.
- Lal, R., 1977. Soil management systems and erosion control. In: Greenland, D.J., Lal, R. (Eds.), *Soil Conservation and Management in the Humid Tropics*. Wiley, New York, pp. 93–98.
- Lal, R., 1979a. The role of physical properties in maintaining productivity of soils in the tropics. In: Lal, R., Greenland, D.J. (Eds.), *Soil Physical Properties and Crop Production in the Tropics*. Wiley, New York, pp. 3–6.
- Lal, R., 1979b. Physical characteristics of soils of the tropics: determination and management. In: Lal, R., Greenland, D.J. (Eds.), *Soil Physical Properties and Crop Production in the Tropics*. Wiley, New York, pp. 7–44.
- Lal, R., 1979c. Mulch. In: Fairbridge, R.W., Finkl, C.W. (Eds.), *The Encyclopedia of Soil Science, Part 1*. Dowden, Hutchinson, and Ross, Stroudsburg, PA, pp. 314–319.
- Lal, R., 1986. Soil surface management in the tropics for intensive use and high and sustained production. In: Stewart, B.A. (Ed.), *Advances in Soil Science*, vol. 5. Springer, New York, pp. 1–109.
- Lal, R., 1987. *Tropical Ecology and Physical Edaphology*. Wiley, New York.
- Lal, R., 1990. Tropical soils: distribution, properties, and management. *Resource Management Optimization* 7, 39–52.
- Lal, R., 1991. Mulch rate effects on maize growth and yield on an Alfisol in W. Nigeria. In: International Soil Tillage Research Organization: 12th International Conference. International Soil Tillage Research Organization, Ibadan, Nigeria, pp. 612–625.
- Lal, R., 2000. Physical management of soils in the tropics: priorities for the 21st century. *Soil Science* 165 (3), 191–207.
- Lal, R., Kang, B.T., Juo, A.S., Moomaw, J.C., 1975. Soil management problems and possible solutions in Western Nigeria. In: Bornemisza, E., Alvarado, A. (Eds.), *Soil Management in Tropical America*. North Carolina State University, Raleigh, NC, pp. 372–408.
- Lambert, J.D.H., Arnason, J.T., 1980. Nutrient levels in corn and competing weed species in a first year milpa, Indian Church, Belize. *Plant and Soil* 55, 415–427.
- Lambert, J.D.H., Arnason, J.T., 1986. Nutrient dynamics in milpa agriculture and the role of weeds in initial stages of secondary succession in Belize, CA. *Plant and Soil* 93, 303–322.
- Lambert, J.D.H., Arnason, J.T., 1989. Role of weeds in nutrient cycling in the cropping phase of milpa agriculture in Belize, Central America. In: Proctor, J. (Ed.), *Mineral Nutrients in Tropical Forest and Savanna Ecosystems*. Blackwell Scientific, Oxford, pp. 301–313.
- Lambert, J.D.H., Arnason, J.T., Gale, J.L., 1980. Leaf-litter and changing nutrient levels in a seasonally dry tropical hardwood forest, Belize, CA. *Plant and Soil* 55, 429–443.
- Leach, H.M., 1999. Intensification in the Pacific: a critique of the archaeological criteria and their application. *Current Anthropology* 40 (3), 311–340.
- Lee, R.D., 1986a. Malthus and Boserup: a dynamic synthesis. In: Colemanand, D., Schofield, R. (Eds.), *The State of Population Theory*. Blackwell, Oxford, pp. 96–130.
- Lee, R.D., 1986b. Population homeostasis and English demographic history. *Journal of Interdisciplinary History* 15 (4), 635–660.
- Lee, R.D., 1987. Population dynamics of humans and other animals. *Demography* 24 (4), 443–465.
- Lee, R.D., 1994. Human fertility and population equilibrium. *Annals of the New York Academy of Sciences* 709, 396–407.
- Leyden, B.W., 1987. Man and climate in the Maya lowlands. *Quaternary Research* 28, 407–414.
- Livi-Bacci, M., 1991. *Population and Nutrition: An Essay on European Demographic History*. Cambridge University Press, Cambridge.
- Livi-Bacci, M., 1992. *A Concise History of World Population*. Blackwell, Cambridge.
- Lohse, J.C., Findlay, P.N., 2000. A Classic Maya house-lot drainage system in northwestern Belize. *Latin American Antiquity* 11 (2), 175–185.
- Lundell, C.C., 1933. The agriculture of the Maya. *Southwest Review* 19, 65–77.
- Maass, J.M., Jordan, C.F., Sarukhan, J., 1998. Soil erosion and nutrient losses in seasonal tropical agroecosystems under various management techniques. *Journal of Applied Ecology* 25 (2), 595–607.
- Marten, G.G., Saltman, D.M., 1986. The human ecology perspective. In: Marten, G.G. (Ed.), *Traditional Agriculture in Southeast Asia: A Human Ecology Perspective*. Westview Press, Boulder, CO, pp. 20–53.
- Martin, S., Grube, N., 2000. *Chronicle of the Maya Kings and Queens*. Thames and Hudson, London.
- Martinez, G., Hansen, R.D., Jacob, J., Howell, W.K., 1999. Nuevas evidencias de las sistemas de cultivo del Preclasico en la cuenca Mirador. In: Laporte, J.P., Escobedo, H.L., de Wasnaver, A.C.M. (Eds.), *XII Simposio de Investigaciones Arqueologicas en Guatemala*. Museo Nacional de Arqueología y Historia and Asociacion Tikal, Guatemala City, Guatemala, pp. 327–336.
- Masson, M.A., 1999. Postclassic Maya communities at Progreso Lagoon and Laguna Seca, northern Belize. *Journal of Field Archaeology* 26 (3), 285–306.
- Matheny, R.T., 1978. Northern Maya lowland water-control systems. In: Harrison, P., Turner II, B.L. (Eds.), *Pre-Hispanic Maya Agriculture*. University of New Mexico Press, Albuquerque, pp. 185–210.
- McAnany, P.A., 1995. *Living with the Ancestors: Kinship and Kingship in Ancient Maya society*. University of Texas Press, Austin.
- Moody, K., 1974. Weeds and Shifting Cultivation. In: *Shifting Cultivation and Soil Conservation in Africa*. Soils Bulletin 24. Food and Agriculture Organization of the United Nations, Rome, pp. 155–166.
- Morley, S.G., Brainerd, G.W., 1956. *The Ancient Maya*. Stanford University Press, Stanford.

- Morrison, K.D., 1994. The intensification of production: archaeological approaches. *Journal of Archaeological Method and Theory* 1 (2), 111–159.
- Morrison, K.D., 1995. *Fields of Victory: Vijayanagara and the Course of Intensification*. Contributions of the University of California Archaeological Research Facility 53, Berkeley.
- Morrison, K.D., 1996. Typological schemes and agricultural change: beyond Boserup in precolonial South India. *Current Anthropology* 37 (4), 583–608.
- Nakano, K., Syahbuddin, 1989. Nutrient dynamics of forest fallows in South-East Asia. In: Proctor, J. (Ed.), *Mineral Nutrients in Tropical Forest and Savanna Ecosystems*. Blackwell Scientific, Oxford, pp. 325–336.
- Nations, J.D., Nigh, R.B., 1980. The evolutionary potential of Lacandon Maya sustained-yield tropical forest agriculture. *Journal of Anthropological Research* 36 (1), 1–30.
- Nepstad, D.C., Uhl, C., Pereira, C.A., Cardosa de Silva, J.M., 1996. A comparative study of tree establishment in abandoned pasture and mature forest of eastern Amazonia. *Oikos* 76, 25–39.
- Netting, R., 1968. *Hill Farmers of Nigeria: Cultural Ecology of the Kofyar of the Jos Plateau*. University of Washington Press, Seattle.
- Nill, D., Nill, E., 1993. The efficient use of mulch layers to reduce runoff and soil loss. In: Mulongoy, K., Merckx, R. (Eds.), *Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture*. Wiley, New York, pp. 331–344.
- Norman, M.J., 1979. *Annual Cropping Systems in the Tropics*. University of Florida Press, Gainesville.
- Nye, P.H., Greenland, D.J., 1960. The Soil Under Shifting Cultivation. Technical Communication No. 51, Commonwealth Bureau of Soils, Commonwealth Agricultural Bureau, Harpenden, UK.
- Nye, P.H., Greenland, D.J., 1964. Changes in the soil after clearing tropical forest. *Plant and Soil* 21, 101–112.
- Okigbo, B.N., Lal, R., 1982. Residue mulches, intercropping, and agrisilviculture potential in tropical Africa. In: Hill, S. (Ed.), *Basic Techniques in Ecological Farming*. Birhauser Verlag, Basel, pp. 54–69.
- Olson, G.W., 1981. Archaeology: lessons on future soil use. *Journal of Soil and Water Conservation* 36 (5), 261–264.
- Peters, W., Neuenschwander, L.F., 1988. *Slash and Burn: Farming in the Third World Forest*. University of Idaho Press, Moscow, ID.
- Pohl, M.D., 1990. *Ancient Maya Wetland Agriculture: excavations on Albion Island, Northern Belize*. Westview Press, Boulder, CO.
- Pope, K.A., Dahlin, B.H., 1989. Ancient Maya wetland agriculture: new insights from ecological and remote sensing research. *Journal of Field Archaeology* 16 (1), 87–106.
- Pope, K.A., Pohl, M.D., Jacob, J.S., 1996. Formation of ancient Maya wetland fields: natural and anthropogenic processes. In: Fedick, S.L. (Ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*. University of Utah Press, Salt Lake City, pp. 165–176.
- Puleston, D., 1974. Intersite areas in the vicinity of Tikal and Uaxactún. In: Hammond, N. (Ed.), *Mesoamerican Archaeology: New Approaches*. University of Texas Press, Austin, pp. 303–312.
- Puleston, D., 1983. *The Settlement Survey of Tikal*. Tikal Reports, No. 13, University Museum Monograph 48. University of Pennsylvania Press, Philadelphia.
- Purata, S.A., 1986. Floristic and structural changes during old-field succession in the Mexican tropics in relation to site history and species availability. *Journal of Tropical Ecology* 2, 257–276.
- Ramakrishnan, P.S., 1989. Nutrient cycling in forest fallows in north-east India. In: Proctor, J. (Ed.), *Mineral Nutrients in Tropical Forest and Savanna Ecosystems*. Blackwell Scientific, Oxford, pp. 337–352.
- Ramakrishnan, P.S., 1992. *Shifting Agriculture and Sustainable Development: An Interdisciplinary Study from North-Eastern India*. UNESCO and Parthenon Publishing Group, Paris and Carnforth, UK.
- Redman, C., 1999. *Human Impacts on Ancient Environments*. University of Arizona Press, Tucson.
- Rice, D.S., 1976. *The historical ecology of Lakes Yaxha and Sacnab, El Peten, Guatemala*. Unpublished Ph.D. Dissertation, Pennsylvania State University.
- Rice, D.S., 1978. Population growth and subsistence alternatives in a tropical lacustrine environment. In: Harrison, P.D., Turner II, B.L. (Eds.), *Prehispanic Maya Agriculture*. Academic Press, New York, pp. 35–61.
- Rice, D.S., 1993. Eighth-century physical geography, environment, and natural resources in the Maya lowlands. In: Sabloff, J., Henderson, J. (Eds.), *Lowland Maya Civilization in the Eighth Century AD*. *Dumbarton Oaks*, Washington, DC, pp. 11–64.
- Rice, D.S., Culbert, T.P., 1990. Historical contexts for population reconstruction in the Maya lowlands. In: Culbert, T.P., Rice, D. (Eds.), *Precolumbian Population History in the Maya lowlands*. University of New Mexico Press, Albuquerque, pp. 1–36.
- Rice, D.S., Rice, P.M., 1990. Population size and population change in the central Peten lakes region, Guatemala. In: Culbert, T.P., Rice, D. (Eds.), *Precolumbian Population History in the Maya lowlands*. University of New Mexico Press, Albuquerque, pp. 123–148.
- Rice, D.S., Rice, P.M., Deevey Jr., E.S., 1985. Paradise lost: classic Maya impact on a lacustrine environment. In: Pohl, M. (Ed.), *Prehistoric Lowland Maya Environment and Subsistence Economy*. *Papers of the Peabody Museum of Archaeology and Ethnology*, vol. 77. Harvard University Press, Cambridge, MA, pp. 91–105.
- Richards, P.W., 1952. *The Tropical Rain Forest*. Cambridge University Press, Cambridge.
- Richter, D.D., Babbar, L.L., 1991. Soil diversity in the tropics. *Advances in Ecological Research* 21, 315–389.
- Ricketson, O.G., Ricketson, E.B., 1937. *Uaxactun, Guatemala: Group E, 1926–1931*. Carnegie Institution of Washington, Pub. 477. Carnegie Institution of Washington, Washington, DC.
- Rosemeyer, M., Schlather, K., Kettler, J., 1999. The *frijol tapado* agroecosystem. In: Hatch, L.U., Swisher, M. (Eds.), *The Managed Ecosystem: The Mesoamerican Experience*. Oxford University Press, New York, pp. 138–144.
- Sabloff, J.A., Andrews, E.W., 1986. *Late Lowland Maya Civilization: Classic to Postclassic*. University of New Mexico Press, Albuquerque.

- Sanchez, P.A., 1976. *Properties and Management of Soils in the Tropics*. Wiley, New York.
- Sanchez, P.O., Logan, T.J., 1992. Myths and science about the chemistry and fertility of soils in the tropics. In: Lal, R., Sanchez, P. (Eds.), *Myths and Science of Soils of the Tropics*. Soil Science Society of America Publication No. 29. Soil Science Society of America, Madison, WI, pp. 35–46.
- Sanders, W.T., 1973. The cultural ecology of the lowland Maya: a reevaluation. In: Culbert, T.P. (Ed.), *The Classic Maya Collapse*. University of New Mexico Press, Albuquerque, pp. 325–366.
- Sanders, W.T., 1979. The Jolly Green Giant in tenth century Yucatan, or fact and fancy in Classic Maya agriculture. *Reviews in Anthropology* 6, 493–506.
- Sanders, W.T., Webster, D., 1994. Preindustrial man and environmental degradation. In: Kim, K.C., Weaver, R. (Eds.), *Biodiversity and Landscapes: A Paradox of Humanity*. Cambridge University Press, Cambridge, pp. 77–104.
- Santley, R.S., Killion, T.W., Lycett, M.T., 1986. On the Maya collapse. *Journal of Anthropological Research* 42 (2), 123–159.
- Saul, F.P., 1972. The human skeletal remains of Altar de Sacrificios: an osteobiological analysis. *Papers of the Peabody Museum of Archaeology and Ethnology*, vol. 63, No. 2. Harvard University, Cambridge, MA.
- Saul, F.P., 1973. Disease in the Maya area: the precolumbian evidence. In: Culbert, T.P. (Ed.), *The Classic Maya Collapse*. University of New Mexico Press, Albuquerque, pp. 301–324.
- Scarborough, V.L., 1993. Water management for the southern Maya lowlands: an accretive model for the engineered landscape. In: Scarborough, V., Isaac, B. (Eds.), *Economic Aspects of Water Management in the Prehispanic New World*. Research in Economic Anthropology Supplement 7. JAJ Press, Greenwich, CT, pp. 17–68.
- Scarborough, V.L., Becher, M.E., Baker, J.L., Harris, G., Valdez Jr., F., 1995. Water and land at the ancient Maya community of La Milpa. *Latin American Antiquity* 6, 98–119.
- Schofield, R., 1985. The impact of scarcity and plenty on population change in England, 1541–1871. In: Rotberg, R.I., Rabb, T.K. (Eds.), *Hunger and History: The Impact of Changing Food Production and Consumption Patterns on Society*. Cambridge University Press, Cambridge, pp. 67–93.
- Schusky, E.L., 1989. *Culture and Agriculture: An Ecological Introduction to Traditional and Modern Farming Systems*. Bergin and Garvey, New York.
- Sharer, R.J., 1994. *The Ancient Maya*. Stanford University Press, Stanford.
- Siemens, A.H., 1982. Prehispanic agricultural use of the wetlands of Northern Belize. In: Flannery, K.V. (Ed.), *Maya Subsistence: Studies in Memory of Dennis E. Puleston*. Academic Press, New York, pp. 205–225.
- Siemens, A.H., Puleston, D.E., 1972. Ridged fields and associated features in southern Campeche: new perspectives on the lowland Maya. *American Antiquity* 37, 228–239.
- Sillitoe, P., 1996. *A Place Against Time: Land and Environment in the Papau New Guinea Highlands*. Harwood Academic, Amsterdam.
- Simmons, C.S., Tarano, J.M., Pinto, J.H.Z., 1959. *Clasificación de Reconocimiento de los Suelos de la Republica de Guatemala*. Ministerio de Educación Publica, Guatemala City, Guatemala.
- Soane, B.D., 1998. Land clearing, drainage, tillage, and weed control. In: Webster, C.C., Wilson, P.N. (Eds.), *Agriculture in the Tropics*. Blackwell Science, Oxford, pp. 113–143.
- Spriggs, M., 1999. Comments. *Current Anthropology* 40 (3), 330–331.
- Stegerda, M., 1941. *Maya Indians of Yucatan*. Carnegie Institution of Washington, Pub. 531, Washington, DC.
- Stone, G.D., 1996. *Settlement Ecology: The Social and Spatial Organization of Kofyar Agriculture*. University of Arizona Press, Tucson.
- Stone, G.D., Downum, C.E., 1999. Non-Boserupian ecology and agricultural risk: ethnic politics and land control in the arid southwest. *American Anthropologist* 101 (1), 113–128.
- Storey, R., 1985. An estimate of mortality in a pre-columbian urban population. *American Anthropologist* 87, 519–534.
- Storey, R., 1997. Individual frailty, children of privilege, and stress in Late Classic Copan. In: Whittington, S.L., Reed, D.M. (Eds.), *Bones of the Maya: Studies of Ancient Skeletons*. Smithsonian Institution Press, Washington, DC, pp. 116–126.
- Storey, R., 1999a. Late Classic nutrition and skeletal indicators at Copan, Honduras. In: White, C.D. (Ed.), *Reconstructing Ancient Maya Diet*. University of Utah Press, Salt Lake City, pp. 169–182.
- Storey, R., 1999b. In: White, C.D. (Ed.), *Reconstructing Ancient Maya Diet*. University of Utah Press, Salt Lake City, pp. 169–182.
- Thurston, H.D., 1992. *Sustainable Practices for Plant Disease Management in Traditional Farming Systems*. Westview Press, Boulder, CO.
- Thurston, H.D., 1994. Slash/mulch systems: neglected sustainable tropical agroecosystems. In: Thurston, H.D. (Ed.), *Tapado. Slash/Mulch: How Farmers Use It And What Researchers Know About It*. Cornell International Institute for Food, Agriculture, and Development. Cornell University, Ithaca, NY, pp. 29–42.
- Thurston, H.D., 1997. *Slash/Mulch Systems: Sustainable Methods for Tropical Agriculture*. Westview Press, Boulder, CO.
- Thurston, H.D., Smith, M., Abawi, G., Kearl, S., 1994. *Tapado. Slash/Mulch: How Farmers Use It And What Researchers Know About It*. Cornell International Institute for Food, Agriculture, and Development. Cornell University, Ithaca, NY.
- Tilman, D., 1988. *Plant Strategies and the Dynamics and Structure of Plant Communities*. Monographs in Population Biology. Princeton University Press, Princeton.
- Tourtellot, G., 1988. *Excavations at Seibal*, Department of Petén, Guatemala. *Peripheral Survey and Excavation*. Peabody Museum, Memoir, 16. Harvard University, Cambridge, MA.
- Tourtellot, G., 1990. Population estimates for Preclassic and Classic Seibal, Petén. In: Culbert, T.P., Rice, D.S. (Eds.), *Precolumbian Population History in the Maya Lowlands*. University of New Mexico Press, Albuquerque, pp. 83–102.
- Tourtellot, G., 1993. A view of ancient Maya settlements in the eighth century. In: Sabloff, J., Henderson, J. (Eds.), *Lowland Maya Civilization in the Eighth Century AD*. Dumbarton Oaks, Washington, DC, pp. 219–242.

- Turner II, B.L., 1976. Population density in the Classic Maya lowlands: new evidence for old approaches. *The Geographical Review* 66, 73–82.
- Turner II, B.L., 1978. Ancient agricultural land use in the central Maya lowlands. In: Harrison, P.D., Turner II, B.L. (Eds.), *Prehispanic Maya Agriculture*. University of New Mexico Press, Albuquerque, pp. 163–183.
- Turner II, B.L., 1979. Prehispanic terracing in the central Maya lowlands: problems of agricultural intensification. In: Hammond, N., Willey, G. (Eds.), *Maya Archaeology and Ethnohistory*. University of Texas Press, Austin, pp. 103–115.
- Turner II, B.L., 1983. *Once Beneath the Forest: Prehistoric Terracing in the Rio Bec Region of the Maya Lowlands*. Westview Press, Boulder, CO.
- Turner II, B.L., 1989. The rise and fall of population and agriculture in the central Maya lowlands: 300 BC to present. In: Newman, L. (Ed.), *Hunger in History: Food Shortage, Poverty, and Deprivation*. Basil Blackwell, Oxford, pp. 178–211.
- Turner II, B.L., 1990. Population reconstruction for the central Maya lowlands: 1000 BC to AD 1500. In: Culbert, T.P., Rice, D.S. (Eds.), *Pre-Columbian Population History in the Maya Lowlands*. University of New Mexico Press, Albuquerque, pp. 301–324.
- Turner II, B.L., Harrison, P.D., 1983. *Pulltrouser Swamp: Ancient Maya Habitat, Agriculture, and Settlement in Northern Belize*. University of Texas Press, Austin.
- Uhl, C., 1987. Factors controlling succession following slash-and-burn agriculture in Amazonia. *Journal of Ecology* 75, 377–407.
- Villa Rojas, A., 1969. The Maya of Yucatan. In: Vogt, E. (Ed.), *Handbook of Middle American Indians*, vol. 7. University of Texas Press, Austin, pp. 244–275.
- Wadell, E., 1972. *The Mound Builders: Agricultural Practices, Environment, and Society in the Central Highlands of New Guinea*. University of Washington Press, Seattle.
- Watters, R.F., 1971. *Shifting Cultivation in Latin America*. Food and Agriculture Organization of the United Nations, Rome.
- Webb, M.C., 1993. Comment on Atran. *Current Anthropology* 34 (5), 694.
- Webster, C.C., Wilson, P.N., 1980. *Agriculture in the Tropics*. Longman, London.
- Webster, D.L., 1985. Recent settlement survey in the Copan Valley, Honduras. *Journal of New World Archaeology* 5, 39–51.
- Webster, D.L., 1993. The study of Maya warfare: what it tells us about the Maya and what it tells us about Maya archaeology. In: Sabloff, J., Henderson, J. (Eds.), *Lowland Maya Civilization in the Eighth Century AD*. Dumbarton Oaks, Washington, DC, pp. 415–444.
- Webster, D.L., 1998. Warfare and status rivalry: Lowland Maya and Polynesian comparisons. In: Feinman, G.M., Marcus, J. (Eds.), *Archaic States*. School of American Research Press, Santa Fe, pp. 311–352.
- Webster, D.L., 1999. The archaeology of Copan, Honduras. *Journal of Archaeological Research* 7 (1), 1–54.
- Webster, D.L., 2002. *The Fall of the Ancient Maya*. Thames and Hudson, London.
- Webster, D.L., Freter, A., 1990. The demography of Late Classic Copan. In: Culbert, T.P., Rice, D.S. (Eds.), *Pre-Columbian Population History in the Maya Lowlands*. University of New Mexico Press, Albuquerque, pp. 37–62.
- Webster, D.L., Freter, A., Gonlin, N., 2000. *Copan: The Rise and Fall of an Ancient Maya Kingdom*. Harcourt Brace, Fort Worth.
- Webster, D., Gonlin, N., 1988. Household remains of the humblest Maya. *Journal of Field Archaeology* 15 (2), 169–190.
- Webster, D.L., Sanders, W.T., Rossum, P., 1992. A simulation of Copan population history and its implications. *Ancient Mesoamerica* 3 (1), 185–198.
- Weiner, J.S., 1972. Tropical ecology and population structure. In: Harrison, G.A., Boyce, A.J. (Eds.), *The Structure of Human Populations*. Clarendon Press, Oxford, pp. 393–410.
- Weischet, W., Caviedes, C.N., 1993. *The Persisting Ecological Constraints of Tropical Agriculture*. Longman Scientific and Technical, Essex.
- White, C.D., 1997. Ancient diet at Lamanai and Pacbitun: implications for the ecological model of the collapse. In: Whittington, S.L., Reed, D.M. (Eds.), *Bones of the Maya: Studies of Ancient Skeletons*. Smithsonian Institution Press, Washington, DC, pp. 171–180.
- White, C.D., Healy, P.F., Schwarcz, H.P., 1993. Intensive agriculture, social status, and Maya diet at Pacbitun, Belize. *Journal of Archaeological Research* 49, 347–375.
- Whitmore, T.M., Turner II, B.L., Johnson, D.L., Kates, R.W., Gottschange, T.R., 1990. Long-term population change. In: Turner II, B.L., Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T., Meyer, W.B. (Eds.), *The Earth as Transformed by Human Action*. Cambridge University Press, Cambridge, pp. 25–39.
- Whittington, S., 1989. Characteristics of demography and disease in low status Maya from Copan, Honduras. Ph.D. Dissertation, Pennsylvania State University. University Microfilms, Ann Arbor.
- Whittington, S., 1999. Caries and antemortem tooth loss at Copan: implications for commoner diet. In: White, C.D. (Ed.), *Reconstructing Ancient Maya Diet*. University of Utah Press, Salt Lake City, pp. 151–168.
- Wilk, R.R., 1985. Dry-season agriculture among the Kekchi Maya and its implications for prehistory. In: Pohl, M. (Ed.), *Prehistoric Lowland Maya Environment and Subsistence Economy*. Harvard University Press, Cambridge, MA, pp. 47–57.
- Wilk, R.R., 1991. *Household Ecology: Economic Change and Domestic Life Among the Kekchi Maya in Belize*. University of Arizona Press, Tucson.
- Wilk, R.R., 1995. Comments. *Current Anthropology* 37 (4), 601–602.
- Wilken, G.C., 1977. Integrating forest and small-scale farm systems in Middle America. *Agro-Ecosystems* 3, 291–302.
- Wilken, G.C., 1987. *Good Farmers: Traditional Agricultural Resource Management in Mexico and Central America*. University of California Press, Berkeley.
- Willey, G.R., Bullard Jr., W.R., Glass, J.B., Gifford, J.C., 1965. *Prehistoric Maya Settlements in the Belize Valley*. Papers of the Peabody Museum of Archaeology and Ethnology, vol. 54. Harvard University, Cambridge, MA.
- Willey, G.R., Shimkin, D.B., 1973. The Maya collapse: a summary view. In: Culbert, T.P. (Ed.), *The Classic Maya*

- Collapse. School of American Research Press, Santa Fe, pp. 457–502.
- Willey, G.R., Smith, A.L., Tourtellot, G., Graham, I., 1975. In: Excavations at Seibal, Department of Peten, Guatemala. Introduction: The Site and its Setting. *Memoirs of the Peabody Museum of Archaeology and Ethnology*, vol. 13. Harvard University, Cambridge, MA.
- Wingard, J.D., 1992. The role of soils in the development and collapse of Classic Maya civilization. Ph.D. Dissertation, Pennsylvania State University, University Microfilms, Ann Arbor.
- Wingard, J.D., 1996. Interactions between demographic processes and soil resources in the Copan Valley, Honduras. In: Fedick, S.L. (Ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*. University of Utah Press, Salt Lake City, pp. 207–234.
- Wiseman, F.M., 1978. Agricultural and historical ecology of the Maya lowlands. In: Harrison, P.D., Turner II, B.L. (Eds.), *Prehispanic Maya Agriculture*. University of New Mexico Press, Albuquerque, pp. 63–115.
- Wiseman, F.M., 1985. Agriculture and vegetation dynamics of the Maya collapse in central Peten, Guatemala. In: Pohl, M. (Ed.), *Prehistoric Lowland Maya Environment and Subsistence Economy*. *Papers of the Peabody Museum of Archaeology and Ethnography*, vol. 77. Harvard University Press, Cambridge, MA, pp. 63–71.
- Wood, J.W., 1998. A theory of preindustrial population dynamics. *Current Anthropology* 39 (1), 99–135.
- Wright, L.E., 1997. Biological perspectives on the collapse of the Pasi6n Maya. *Ancient Mesoamerica* 8 (2), 267–274.
- Wright, L.E., Wright, C.D., 1996. Human biology in the Classic Maya collapse: evidence from paleopathology and paleodiet. *Journal of World Prehistory* 10 (2), 147–198.
- Wrigley, G., 1982. *Tropical Agriculture: The Development of Production*. Longman, London.