Chapter 2

The Changing Global Environment and the Lowland Maya: Past Patterns and Current Dynamics

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INTRODUCTION

Images of the ancient Maya focus on a culture that built science, art, and architecture equivalent to the most advanced civilizations of their time. This culture, however, also experienced an almost complete political and cultural collapse of enormous magnitude, which resulted from the overuse of a fragile environment during periods of rapid climate change. Unfortunately, our images of the ancient Maya do not convey the unique aspects of both the rise and the change in culture of the region, or what lessons we can apply to our own times. Forests in the Maya region are actually quite resilient, as shown by their high biodiversity and stability in the face of continuing disturbance. The Maya people are not gone—they are the largest indigenous group of Native Americans in North America. As with most cultures, they have changed; their historical roots and current practices, however, have much to teach the rest of us.

The Maya civilization was born during one climate regime, expanded during a different climatic period, then retracted and changed over a third. The ancient Maya dramatically altered their surroundings, and then abandoned the more advanced scientific and artistic elements. They dropped drastically in population and returned to a simpler lifestyle—more

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susceptible to their surroundings, but likely also more attuned to their environment. As such, they developed institutions and technologies based on one set of ecosystem parameters, expanded and enhanced their population under different ecosystem properties, and then finally abandoned what had been a successful lifestyle under a third set of ecosystem limitations.

The failure of the cultural attributes of the Classic period to provide for existence during the changing conditions of the Postclassic period should not be a surprise. What should be of greater interest is developing an understanding of how the Maya persisted through many different environmental and cultural changes. Despite very high human population densities, elements of the wildland ecosystem persisted, adequate to reclaim most of the region when human numbers declined and areas were abandoned. This response to environmental change appears to be rather unique among human adaptations. As we change our own environment, are there lessons that can be learned from the Maya experience? If so, to what extent can we compare those changes that the Maya survived with changes prevalent in our own time?

Cultural practices may have important implications to wildland ecosystems. Religion is tightly coupled to food production and stability (agri-*culture*) in the Maya culture just as elsewhere. Similarly, we must search for solutions to cope with environmental change if wildland ecosystems and high levels of biodiversity are to persist. Terrestrial tropical ecosystems appear to hold important keys to both the release and sequestration of carbon (C), as well as to global climate. The functioning of ecosystems in the Yucatán Peninsula, both past and current, appears to hold important clues to these keys.

In this chapter, we provide an overview of the ecosystem characteristics of the Yucatán Peninsula, evaluate those changes that may have been critical to supporting the developing civilization as well as influential in its collapse, and provide some projections of the types of changes underway for our own time.

PAST ENVIRONMENTS AND THE YUCATÁN PENINSULA

Distinct Maya cultural activity can be traced at least three thousand years into the past, which coincided with rather dramatic shifts in climate. We introduce only the types of change here; further detail is presented elsewhere in this book.

Hunter-gatherers used the more arid shrub/grassland regions of the Yucatán Peninsula as far back as the Pleistocene epoch. As the climate grew wetter and warmer, seasonal tropical forests became more expansive—creating a difficult region in which large-scale agriculture could establish.

In drier regions of North America and South America, such as the desert of Peru, ancient civilizations arose some 4,000 years ago that were equivalent to those in Africa and the Middle East (Solis, Haas, and Creamer 2001). Three millennia ago, Preclassic civilizations arose in southern Mexico and Guatemala coincident with a drying of the environment. Although surface waters were still present, levels of inundation were less apparent than today. Severe drought coincided with the collapse of the Classic Maya civilization, but the returning wetter regimes appear not to have supported any recovery of the earlier urban life in the southern lowlands. In the northern lowlands, Maya civilization changed dramatically, supporting first an urban civilization, then smaller cities and village lifestyles that survived through Spanish colonization, and up until today.

The ancient Maya faced one problem that persists today—namely, conversion of land from wild forest to one supportive of agricultural crops. Despite the use of forest resources, opening fields for maize, beans, squash, and other crops requiring high light intensity was essential. To support the incredibly high population density that existed in the past, vast amounts of land were converted from forest to cultivated lands. Although the ancient Maya retained certain trees such as *Ceiba pentandra* in the middle of agricultural fields, the problem of feeding large populations required extensive land clearing. This is apparent in the changing pollen analysis during the times of human occupation.

One particular difference between the environment of the ancient Maya and today needs further consideration. During the rise and fall of the Maya civilization, the atmosphere contained less than 250 parts per million (ppm) of carbon dioxide (CO_2). It had likely been as low as 190 ppm during the Pleistocene, gradually rising to about 250 ppm during the Industrial Age, when the dramatic increases that are characteristic of our own times became apparent. This means that during the Maya agricultural hiatus, CO_2 was likely a limiting factor—not an excess resource. Both land conversion and CO_2 concentrations have major impacts on how ecosystems work that are crucial to understanding past human activities and predicting where the Yucatán Peninsula is headed today.

THE EL EDÉN TROPICAL SEASONAL FOREST: CURRENT ECOSYSTEM STRUCTURE

Little is understand of the functioning of wildland ecosystems in the Maya lowlands. Models of ecosystem processes have been generated in the Florida Everglades, or in areas such as La Selva in Costa Rica, or Barro Colorado Island in Panama. While these areas provide insights into tropical ecosystem theory, the details of how the ecosystems work remain largely unknown.

A site in southeastern Mexico has studying for soil and plant dynamics in conjunction with other ongoing research on biodiversity and restoration. The site is located at the El Edén Ecological Reserve, situated within northern Quintana Roo, Mexico. This site contains a wide range of environmental conditions, from cenotes and wetlands to upland mature forests and secondary forests. These conditions represent most ecosystem types in the area, with the exception of coastal areas. As a test case for environmental change and ecosystem functioning, we will examine the information gathered largely at this site and in the surrounding areas.

Climate

The climate at El Edén is characterized by an extended winter/spring drought, with the wet period commencing in June or July. The total precipitation averages 1,200 millimeters/year (mm/yr.). This results in a tropical seasonal forest. The wetlands result from a high water table and a flow northward through the limestone. In the wet season, the water table is high enough that the wetland resembles a slow-moving, northward-flowing river. During the dry season, only the cenotes contain standing water.

The climate is strongly influenced by the Gulf of Mexico, the Caribbean Sea, and the North Atlantic. Importantly, we have found little evidence that El Niño has a major impact on the Yucatán Peninsula. La Niña, however, may play a major role; during La Niña periods, hurricanes appear to peak, and almost every major hurricane during recorded history has appeared during a La Niña period. Water inputs also support the influence of La Niña (Figure 2.1). Precipitation is consistently higher in La Niña periods than during El Niño years.

Soils

The soils of El Edén are typical of the Yucatán Peninsula. The forest soils consist largely of limestone covered with a thin [1–4 centimeters (cm)] veneer of soil. Most plant growth exists in small potholes filled with extremely rich soil that is really a mulch mix. These soil patches are extremely high in organic matter (O.M.), ranging from 15 to 30% organic carbon (C), and are surprisingly rich in nutrients that support rapid plant growth (Table 2.1).

In the uplands, a layer of red soil can be found. We have not studied this soil in detail, but it contains a high clay content and holds considerable moisture. In other regions, similar soils tend to be high in iron (Fe), deficient in available phosphorus (P) and organic carbon (C), and can become lateritic [i.e., high in aluminum (Al)] when repeatedly cropped.

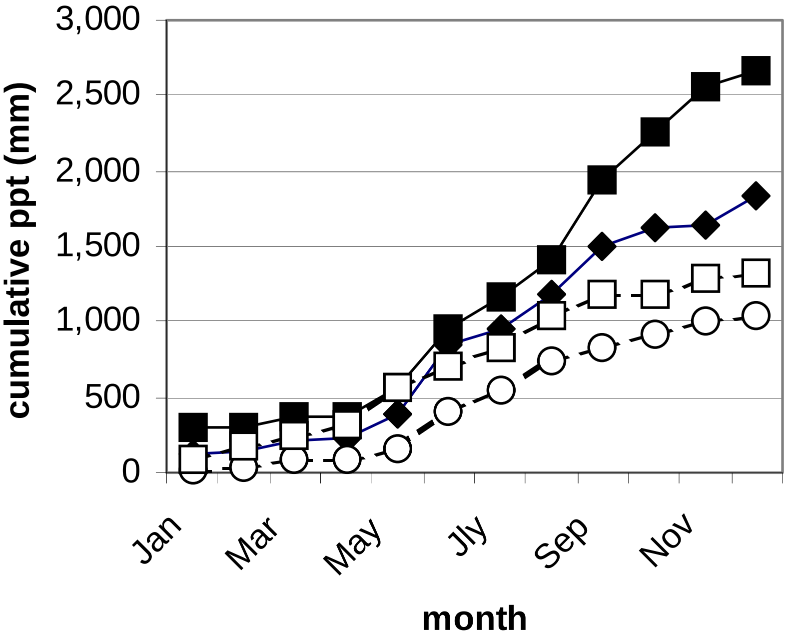

FIGURE 2.1. Comparative precipitation (ppt) of La Niña years (1964 [closed diamond], 1988 [closed square]) versus El Niño years (1991[open circle], 1997[open square]) at Kantunilkin, Quintana Roo, Mexico.

In the wetlands, the soils tend to be largely muck with high clay content, relatively rich in phosphorus (P) but low in nitrogen (N) (Schultz, unpublished data). In one sense, this is surprising in that there is a very high density of cyanobacteria that are rapidly fixing atmospheric nitrogen (N_2). This may be due to high rates of denitrification. Conditions for denitrification, high organic matter, warm temperatures, and low oxygen tensions are perfect for rapid rates.

Soil Organisms

Although we understand little about the soil organisms in these regions, what we do know is very interesting. In the acahual and in the mature forests at El Edén, the dominant type of mycorrhizae are arbuscular mycorrhiza (AM). In this system, the fungal hyphae are very dynamic—extending outward a few centimeters from a root and extracting largely plant-available nutrients, but turning over rapidly. The fungal hyphae also respire, locally mineralizing phosphorus (P) as the increasing CO_2 in solution becomes bicarbonate (Figure. 2.2).

In patches of mature forest, older acahual, and especially in the tintal, we also find species of *Amanita*, *Boletus*—even *Suillus*—as well as other genera of ectomycorrhizal fungi. The presence of these fungi indicates that

TABLE 2.1. Soil nutrients in the research plot at El Edén Ecological Reserve. Soil samples were collected at four different times: from the mature forest, before burning (Preburn), in the restoration plot following burning (Postburn), and at two years after planting

	15 June 1997	17 June 1997	4 July 1997	12 July 1999
	Mature Forest		Restoration Plot	
	Inoculum	Preburn	Postburn	At two years
pH	7.2	7.7	7.6	7.5
ug/g total P	710.6	564.6	591.1	nd
S.E.	88.0	55.2	49.8	
ug/g extr P	20.2ab	29.1b	29.4b	14.5a
S.E.	6.4	3.0	2.5	1.6
% O.M.	26.8a	34.0a	15.9b	43.2c
S.E.	6.8	1.2	0.7	1.1
% total N	2.04a	1.39a	1.52a	0.87b
S.E.	0.65	0.08	0.09	0.05

nd = no data; P = phosphorus; N = nitrogen; O.M. = organic matter; S.E. = [**standard error of the mean**]

nutrients, particularly nitrogen (N), are likely directly transported from litter to plants in the form of amino acids, not only following mineralization. In some cases, mats can be distinguished with large amounts of thick, white hyphae—suggesting that oxalates are abundant that bind calcium (Ca^{2+}) and other cations. These organic acids bind and concentrate cations such as Ca^{2+} and Al^{3+}, which simultaneously release the complexed phosphorus (P) (see fig. 2.2). Orchids have their own distinctive mycorrhizal fungi that extract nutrients and often sugars and carbohydrates from the substrate on which they are growing. While these plants are not known to be of high importance to forest ecosystem dynamics, they are commercially important and interesting from the perspective of both biodiversity and conservation.

Nitrogen-fixing bacteria that are symbiotic with legumes play an extremely crucial role in these forests. Most of the rapidly growing tree seedlings are legumes, and examination of these plant roots reveals high densities of red nodules, which indicate active fixation. We do not know much about the diversity of these bacteria, their species associations, and their efficiencies; we do know, however, that these bacteria are so efficient

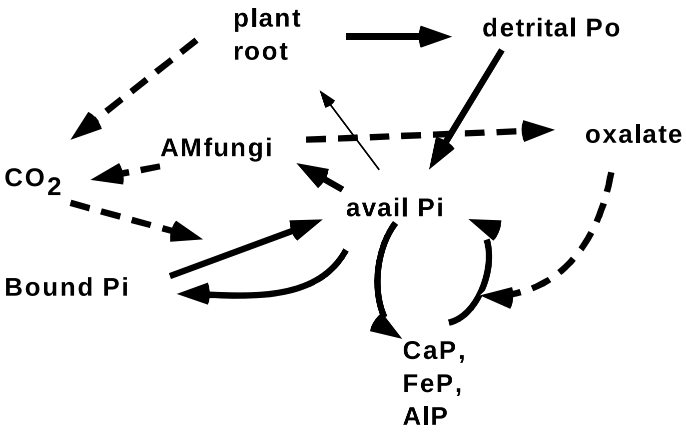

FIGURE 2.2. Phosphorus (P) cycling in the forest soils of El Edén. (Source: Adapted from Allen 1991.)

that the N/P ratios of most of the acahual forest trees range from 20 to 40, which suggest that the plants tend to be deficient in P, but not N.

Together, N_2-fixing bacteria and mycorrhizal fungi are critically important for these communities. Not only do these organisms aid the nutrient status of their immediate host, but the mycorrhizal fungi also connect multiple plants. Nitrogen has been fixed by a N_2-fixing host (beans), and then transported to a second host (maize) by the fungi (Bethlenfalvay et al. 1991). We have recently found that deep water can be taken up by a host plant, then transported to a mycorrhizal fungus by hydraulic lift (Querejeta, Egerton-Warburton and Allen, unpublished data), which allows nutrient uptake to occur in dry soils. We are currently attempting to determine if this water can be transported to a neighboring plant.

Vegetation Structure

Although wildland communities are described in detail elsewhere in this volume, there are some additional issues that are critical for discussion here. These include the photosynthetic pathway and water-use efficiency, as well as rooting structure and water access.

First, the large majority of the plants are C_3, or cool-season, species. In the presence of light, the stomata of these plants open and allow water to escape, while simultaneously allowing CO_2 to diffuse in. Through the Calvin cycle, CO_2 is fixed into glucose in the mesophyll cells immediately inside the stomata and throughout the leaves. Leaves maintain optimum temperatures (20–30^{o}C) through transpiration, but this entails sensitivity to drought. Thus, water loss can be high. Water-use efficiency (WUE) is defined as the number of water (H_2O) molecules lost to CO_2 molecules gained. In most C_3 plants for this region today, a general figure is around

318 H_2O molecules per CO_2 molecule. This number will become important later in the discussion.

Second, a few of the forest succulents (e.g., Bromeliaceae) contain the Crassulacean Acid Metabolism (CAM). CAM plants open their stomata at night and fix CO_2 into malate. Even though the stomata are closed during the daytime, enough light is available for the malate to be converted back into CO_2, and then fixed into glucose through the Calvin cycle. WUE can be quite high, as water is not lost from the plant during the day when transpiration rates are high. Few plants in the wildlands are C_4, or warm-season, plants. C_4 plants have a distinct anatomical and physiological shift. In the mesophyll cells, CO_2 is fixed into malic acid and aspartic acid. These C_4-acids are then transported to bundle sheath cells where glucose is made. These plants are very efficient in obtaining CO_2 at low concentrations, and therefore have rather high WUE. They also efficiently fix CO_2 up to 35^oC. Only a few grasses in the wildlands are C_4, but maize is a C_4 plant, which could have major implications for ancient agriculture.

Third, the structure of forest roots is also of interest in areas where water is especially crucial. Forests are largely C_3, releasing large amounts of water, and thus have lower WUE. Some of these trees have deep roots that access water, especially in the northern part of the Yucatán Peninsula where the water table is relatively shallow. Observations such as the drawing by Catherwood of the Cave at Bolonchen (see Stephens 1843) show that roots extend deep into the limestone. Data from El Edén (Figure 2.3) show that there are some important differences among species. Some, such as *Ceiba pentandra* or *Leucaena leucocephala*, maintain a high water potential (low water stress) into the dry season. This indicates that these plants have deep roots tapping into the groundwater. Others, such as *Havardia albicans* or *Acacia penatula*, undergo severe drought stress, which suggest the presence of shallow, spreading roots that exhibit rapid growth during the wet season. These are different strategies for coping with the dry season.

Agriculture

Increasingly, lands are being converted from forest to agricultural production. In the more traditional agricultural practices, this conversion involves short-term use followed by a long-term fallow rotation system. In the Yucatán Peninsula throughout the pre-Hispanic period, the Maya did not use large animals as manure producers, which would have allowed a three-field rotation system. Thus, the land-ownership concept that existed in Europe differed radically from that in the Maya lowlands. Fertility resulted from N_2 fixation by multicropping with legumes, and from fallow periods that extended upwards for about two decades.

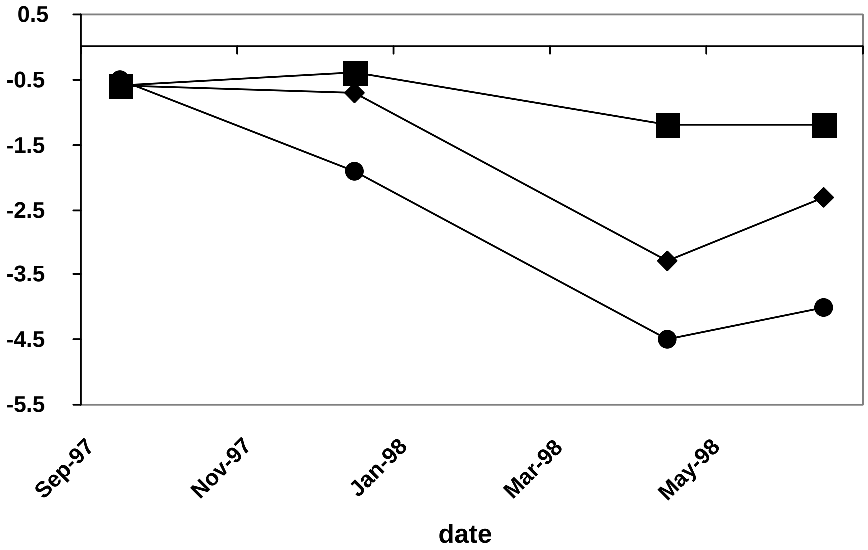

FIGURE 2.3. Water potentials (measured in MPa) of plants from a mature forest and seedlings from a restoration experiment at El Edén; measurements were taken in the wet season and continued through a dry season. Shown are *Ceiba pentandra* in the restoration plots (square), and *Havardia albicans* in the restoration plots (diamond) and in the forest (circle). *C. pentandra* is an example of a species with rapid and deep root growth, while *H. albicans* has shallow, spreading roots.

There is an additional consideration. Anderson (pers. comm.) pointed out that during traditional agriculture, some species of trees (e.g., *C. pentandra*) were left alone, as well as many resprouts. Some concern has been expressed as to why these trees were untouched because they compete with crops for light and nutrients. Were these left for shade, for religious reasons, or for other unknown purposes?

There may, however, be other compelling reasons. Of the mixture of species left untouched, some species appear to have roots that reach groundwater. For these trees, there is a high likelihood that hydraulic lift occurs during the early part of the drying cycle. Water is picked up in the deeper roots and is transported horizontally to the surface soils during the night (Jackson, Sperry, & Dawson 2000). As both the trees and crop plants form arbuscular mycorrhizae, the possibility that this water could play a critical role in maintaining the water status of nearby crop plants cannot be underestimated.

In the southern and western part of the peninsula, agricultural techniques are changing. Mechanized agriculture (where possible) and commercial fertilizers have change the system to a monoculture in which N_2 fixation within a maize field (from co-cropped beans) has been eliminated. If it is assumed that the remaining trees are removed, then any importance of hydraulic lift is lost. Often, because of increasing demands for food, the fallow period is eliminated with unknown consequences.

ECOSYSTEM DYNAMICS: CURRENT VERSUS PAST

Water dynamics regulate virtually all processes in the Yucatán Peninsula, as with most locations. Rainfall tends to be high, but very seasonal—increasing from the northern lowlands to the southern lowlands, and then into the highlands. This seasonality, coupled with the porous limestone and lack of soil, means that little water is held in the surface for plant use. In some regions such as the Yalahao, however, the groundwater is close enough to the surface to be important. These characteristics are essential to understanding the dynamics of these ecosystems.

Three features in water dynamics are crucial to comparing the ecosystems of ancient times with those of today. The first (and foremost) feature is probably the differing CO_2 regimes of 1,500 years ago and today. Prior to the Industrial Revolution, atmospheric CO_2 was only about 210 to 250 ppm (versus 370 today). WUE would have been extremely poor for C_3 plants. For example, for each CO_2 molecule fixed in about 900 A.D., 532 molecules of H_2O were lost. This compares to a H_2O:CO_2 ratio of 318:1 today and, potentially, a ratio of 197:1 by the end of the next century. One impact would have been that during the Classic period, failure or low rainfall would have been much more devastating to production of C_3 crops (beans, squash, and chilies) and trees than today.

One important exception is C_4 maize. C_4 plants have a high WUE that produces much more mass per molecule of H_2O than an equivalent C_3 plant. This is important to agriculture and human nutrition as well. During drought years, one could readily envision a steady production in maize, with other crops (e.g., beans and squash) declining. How this might play into human nutrition is speculative; during marginal years and times of social unrest, however, this exception could prove important.

A second impact on water dynamics is the forest itself. Because of the high leaf area of the forest, transpiration rates can exceed the rates of water loss from open pans. As one moves inland, greater amounts of water in the atmosphere continue to come from vegetation, not from the ocean (Hayden 1998). This process has clearly been demonstrated in the Amazon basin. This is also apparent in weather satellite images and in precipitation patterns in the Yucatán (see Orellana, 1999).

In inland areas such as the Petén region, then, a large fraction of atmospheric water and precipitation likely was derived from transpiration during Preclassic and Early Classic Maya times. With a low WUE across the forest, and an onshore breeze associated with inland heat, a large fraction of the atmospheric water would have come from the forest itself. With extensive deforestation (bare soil) and increasing coverage of the land with C_4 maize, as the dominant plant, this water would not necessarily be put back into the atmosphere at inland regions.

The final pieces in this puzzle are the microbial symbionts themselves, particularly mycorrhizal fungi and N_2-fixing bacteria. Under low atmospheric CO_2 concentrations, mycorrhizae are limited in C (Treseder & Allen 2000). With drought, these fungi also do not produce the extensive hyphal networks necessary to take up limiting nutrients efficiently. These fungi are responsible for creating soil aggregates that are essential to soil structure and moisture-holding capacity, and soil aggregates are reduced with low atmospheric CO_2 levels (Rillig et al. 1999). Mycorrhizal fungi are also very sensitive to disturbance and land clearing. Experimental tests have demonstrated that levels of these fungi are dramatically reduced if forests are removed by burning (E. Allen et al., this volume). These fungi are responsible for most of the P uptake into plants. Phosphorus is not readily mobile in the soil solution. The extensive hyphal network radiates out and transports the available P back to the host in exchange for sugars. In calcareous soils or high cation soils, the CO_2 respired by these fungi weather P and also produce organic acids that maintain the P in solution for uptake (e.g., Allen et al. 1996).

Nitrogen fixation into crops such as beans for essential amino acids is energy limited, and, thus, water limited. A single protein molecule such as hemoglobin requires 146 molecules of NH_3^+, which needs a large amount of energy (12 ATPs/N_2 fixed) and, thus, assimilated C. Assuming that the average Maya required 50 g protein (as today), gained mostly from beans, then the plants would have transpired 44 liters (l) of water for CO_2 fixation (compared with 26 l today). As drought proceeds, photosynthesis and N_2 fixation rapidly decline, and so does protein from agricultural sources. This places an additional burden on hunting and increases the sensitivity of the population to game depletion.

Thus, virtually all ecosystem processes—from forest nutrient turnover, to fertility, to protein—is dependent on the water regime of a region. The forests are not only users of regional water, but also creators. We are learning that water is coupled tightly to the functioning of an ecosystem. Changing the proportion of land in various components (e.g., converting wetlands and forests to large-scale agriculture) had the potential to alter virtually every aspect of agricultural production during the Classic period.

As WUE declines with decreasing CO_2 levels, nutrient-use efficiency increases. N and P concentrations go up at 250 ppm CO_2, as compared with ambient (Allen, unpublished data). This could mean two things for the ancient Maya compared with today. First, following opening of a forest for crop production, nutrients were probably not limiting. Even today, P and N concentrations in soil, even following burning, are very high (see Table 2.1). Estimates of nutrient removal suggest that, even with many years of agriculture, nutrient levels were unlikely to be limiting in at least northern Yucatán. With continual production, however, cation immobilization of P is still likely important. In terms of long-term agriculture, we still suggest that nutrients would not limit production as much as in today's environment. The increasing N concentration, however, has a secondary effect. Thus, secondly, insect and pathogen activity may increase markedly in response to increasing N concentration of the leaves because leaf material is simply more nutritious. With increasing N, however, plants can also produce more secondary defense chemicals, which, in turn, would negatively affect grazers (and humans). These dynamics clearly need better understanding of basic plant ecological interactions.

CURRENT AND PROJECTED ENVIRONMENTAL CHANGE AND THE YUCATÁN PENINSULA

Global concentrations of CO_2 are rising dramatically. From 250 ppm pre-Industrial Age, to over 370 ppm today, this exponential rise is expected to continue well into the next century, rising to at least 550 ppm. Although some models show a leveling off at around 550 ppm, these estimates are based on some dramatic changes in cultural practices that are not supported by the current political climate. Elevated CO_2 levels have some benefits for crop production (discussed above), but also have potential dramatic consequences to climate and ecosystem processes.

The changing global climate is not only a function of elevated CO_2 from North American manufacturing and European industry. Forest clearing not only directly increases CO_2 loss from decomposing organic matter in the soil, but also reduces the ability of the ecosystem to absorb CO_2. As previously discussed, deforestation also potentially reduces transpiration and dramatically affects soil processes. Finally, increasing urban growth and industrialization fragments the region and places increasing demands on local production for food and water.

We have evaluated the data from two sources near El Edén to better understand the potential effects of global climate change issues on the region of our study area. These two sources are the weather records from Kantunilkin and Solferino. With a twofold increase in CO_2 concentrations (i.e., 350 to 700 ppm) because of rising ocean-heat loading, rainfall in the Caribbean region is expected to increase 20 to 40% with a 1–2^{o}C rise in annual temperature and a 5 mm/yr. increase in sea level. Over the last 200 years, CO_2 concentrations rose 48%, with most of that increase within the last 50 years. Both sites have experienced changes in climate over the last 40 years. At Kantunilkin, precipitation has increased an average of 6.2

mm/yr. since 1961, at *p* = 0.23. While this is of marginal significance, the monthly pattern of that increase is of much greater interest. The bulk changes occur in April, May, and November (fig. 2.4). These are significant enough to warrant the need for additional monitoring. These changes also occur at the end of the growing season and could be adequate to extend the growing season on either end. At Solferino, the precipitation pattern is similar, but not statistically significant.

Minimum temperatures also provide an interesting clue about a potentially changing environment (fig. 2.5). At Solferino, the minimum temperature has increased since 1970 for each month except March. During the rainy season, these increases are highly significant (June, 0.105^{o}C/yr., $p < 0.0001$; July, 0.09^{o}C/yr., $p = 0.003$; August, 0.106^{o}C/yr., $p = 0.0002$; September 0095^{o}C/yr., $p < 0.0001$; October, 0.062^{o}C/yr., $p = 0.11$). Minimum temperatures reflect the dew point temperatures; as the relative humidity rises, so does the minimum temperature associated with the increasing ocean temperatures.

At Kantunilkin, however, the opposite pattern emerges. Since 1961, minimum temperatures have declined in every month except November. This is especially apparent in June (–0.103^{o}C/yr, $p = 0.003$), July (–0.075^{o}C/yr, $p = 0.004$), August (–0.083^{o}C/yr., $p = 0.011$) and September (–0.65^{o}C/yr., $p = 0.015$). Why the difference? The sites are only a few kilometers apart, and the precipitation is increasing at Kantunilkin. The most likely explanation exists in recent satellite images. The new moderate resolution imaging spectroradiometer (MODIS) satellite clearly shows a brown region extending eastward across the northern part of the Yucatán

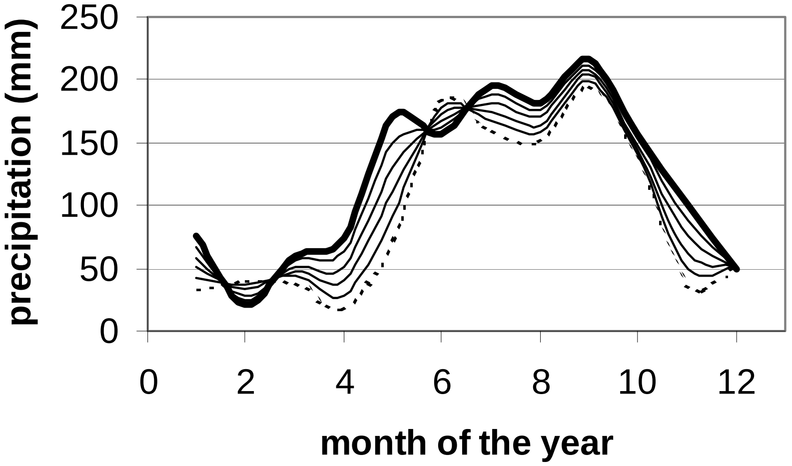

FIGURE 2.4. Precipitation structure at Kantunilkin for decadal intervals from 1960 (dashed line) to 2010 (solid heavy line). These projections are based on the increasing rates of precipitation since 1961 in the growing season, including April (*p* = 0.12) and May (*p* = 0.15), and again at the end of the growing season in November (*p* = 0.12).

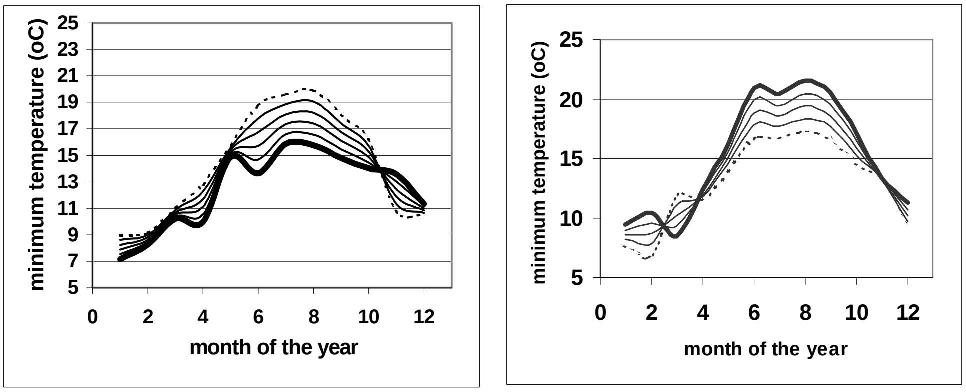

FIGURE 2.5. Minimum temperature structure at Kantunilkin (left) and Solferino (right) for decadal intervals from 1960 (dashed line) to 2010 (solid heavy line). At Kantunilkin, these projections are based on the decreasing minimum temperatures since 1961 during the growing season, which includes June, July, August, and September (see text for details). At Solferino, these projections are based on the increasing minimum temperatures since 1971 in March, April, May, October, and November (see text for details).

Peninsula, encompassing Kantunilkin, whereas Solferino has remained green (NASA 2001). Reports indicate that the forest largely remains intact at Solferino, whereas the landscape surrounding Kantunilkin has been increasingly deforested for agricultural production. These observations correspond to the areas that have become agricultural during the past few decades, as well as to increasing secondary forest vegetation. As discussed earlier, relative humidity (and, thus, dew point) is highly dependent not only on the moist air from the ocean, but also increasingly from the forest vegetation itself. This would be especially apparent during the peak of the growing season when the stomata are wide open.

These results are crucial to the global climate scenarios and for regional impacts. Rising CO_2 concentrations mean more water, rising sea levels, and increased chances of flooding. Recent research has shown that the forests in this hemisphere (and especially in North America) are critical CO_2 sinks. We do not know all of the details (Malhi & Grace 2000), but much of the increasing carbon goes below ground and is associated with mycorrhizal fungi in a manner that may be similar to what we have found in temperate regions (Rillig et al. 1999). Just as important, deforestation changes the sequestration of carbon both by directly eliminating the forest, but also likely by the changes in soil organisms in response to the ecosystem adjustments to perturbation.

Both agricultural and vegetation maps show dramatic increases in agricultural area (fig. 2.6) and secondary forest (see vegetation maps of Gonzalez-Iturbe and colleagues, in Olmstead 1999). These will reduce the

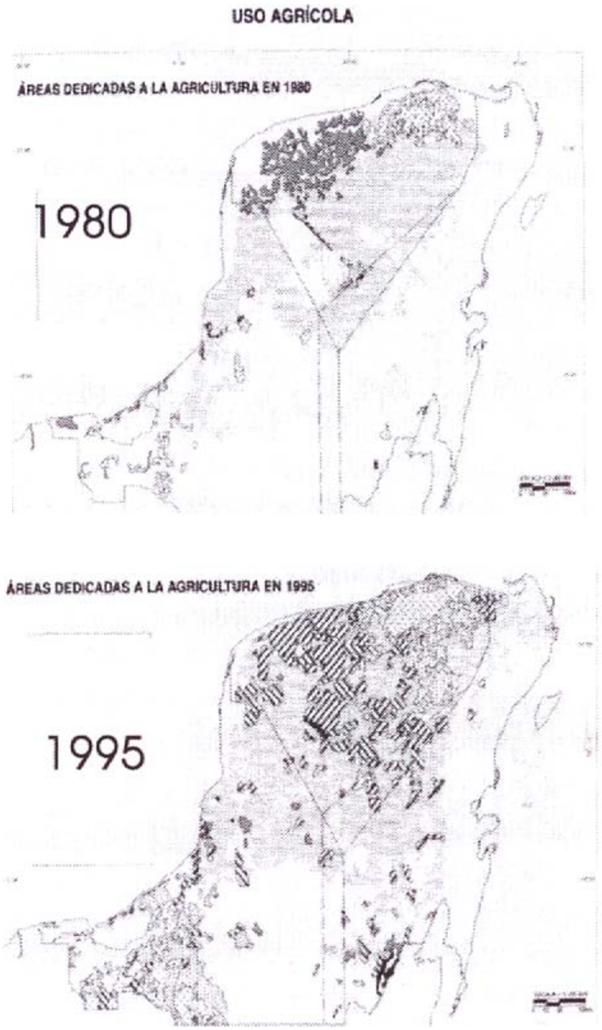

FIGURE 2.6. Changing plant cover in northeastern Yucatan Peninsula, showing changes in agricultural lands between 1980 and 1995. The striped regions are permanent or rotational agriculture. For other finer resolution, see original reference. (Source: Redrawn from Gilberto XIX AKE' 1999).

carbon sink strength. The dramatic increases in protected areas are just as important, however, because they protect the carbon-sequestration capacity of the region. Careful agricultural, wildland, and forest management practices (demonstrable in the Yucatán as nowhere else) have the potential to make observable inroads, or at least reductions, in our degrading global environment.

The global environment may be critical for developing scenarios of climate change for the Yucatán Peninsula (Kerr 2001). El Niño signals can be found in the fossil records and suggest that this phenomenon may be sensitive to the changing global environment. To our knowledge, there are no signals known for La Niña patterns. There is some speculation, however, that La Niña may be increasing in strength and frequency as the Pacific gyre changes. Hurricane frequency is expected to increase with increasing La Niña activity, and intensity is expected to increase with the rising global sea surface temperatures. Based on these projections, we can expect more frequent and intense hurricane activity, increasing disturbance by flooding and wind, and rising sea levels.

CONCLUSION

Past climates have dramatically affected human activities in the lowland Maya regions. The Maya civilization arose during one climate regime, expanded and flourished during a second climatic shift, and then retracted and changed over a third. Characteristics changed dramatically with severe drought, and the recovery in human activities changed forms. Climate is continuing to change. Importantly, the critical shifts today may well be induced by humans—not by the Maya locally, but certainly worldwide—and, in many cases, in ways that the Maya changed their surroundings a millennium ago.

Elevated CO_2 concentrations (through its effects on water-use efficiency and nutrient-use efficiency) and deforestation (through loss of habitat for wildlands, and possible effects on water recycling) could have rather dramatic effects on all natural and agricultural resources of the region. These need to be considered in any land-use planning—both for protection of wildland resources, and for the impacts on agriculture and forestry.

Finally, the region itself may be a critical one for the remainder of the globe. Tropical North America is being recognized as a key sink for elevated CO_2 levels. The large reserves that protect wildlands, forestry, and integrated community activity may hold clues not only to how people in regions around the globe should behave, but also how we are linked around the globe.

LITERATURE CITED

Allen, M.F. 1991. The ecology of mycorrhizae. Cambridge University Press, Cambridge.

Allen, M. F., C. Figueroa, B. S. Weinbaum, S. B. Barlow, and E. B. Allen. 1996. Differential production of oxalates by mycorrhizal fungi in arid ecosystems. *Biology and Fertility of Soils* **22**: 287–-292.

Bethlenfalvay, G. J., M. G. Reyes-Solis, S. B. Camel, and R. Herrera-Cerrato. 1991. Nutrient transfer between the root zones of soybean and maize plants connected by a common mycorrhizal mycelium. *Physiologia Plantarum* **82**: 423–-432.

Gilberto XIX AKE'. 1999. USD Agricola. Universidad Autonoma de Yucatan. At-las de proceson territoriales de Yucatan (p. 200). Medico: Preesa.

Hayden, B. P. 1998. Ecosystem feedbacks on climate at the landscape scale. *Philosophical Transactions of the Royal Society of London B Biological Sciences*. **353**: 5–-18.

Jackson, R. B., J. S. Sperry, and T. E. Dawson. 2000. Root water uptake and transport: uUsing physiological processes in global predictions. *Trends in Plant Science* **5**: 482–-488.

Kerr, R. A. 2001. The tropics return to the climate system. *Science* **292**: 660–-661.

Malhi, Y., and J. Grace. 2000. Tropical forests and atmospheric carbon dioxide. *Trends in Ecology and Evolution* **15**: 332–-337.

National Aeronautics and Space Administration (NASA). 2001. Earth Observatory. Available online : <http://earthobservatory.nasa.gov/Library/Measuring Vegetation/measuring_vegetation_4.html>

Olmsted, I.C. 1999. Vegetacion. In Universidad Automona de Yucatán. Atlas de proceson territoriales de Yucatan (pp 183- 194). Mexico, Preesa.

Querejeta, J. I., L. Egerton-Warburton, and M. F. Allen. 2003. Direct nocturnal water transfer from oaks to their mycorrhizal symbionts during severe soil drying. *Oecologia*. In Press.

Orellana,R. 1999. Evaluacion climatica. In Universidad Automona de Yucatán. Atlas de proceson territoriales de Yucatan (pp 163-182). Mexico: Preesa.

Rillig, M. C., S. F. Wright, M. F. Allen, and C. B. Field. 1999. Rise in carbon dioxide changes soil structure. *Nature* 400:628.

Solis, R. S., J. Haas, and W. Creamer. 2001. Dating Caral, a preceramic site in the Supe Valley on the central coast of Peru. *Science* **292**: 723-–726.

Stephens, J. L. 1843. *Incidents of travel in Yucatan*. Edited by K. Ackerman. Washington DC: Smithsonian Institution Press.

Treseder, K. K., and M. F. Allen. 2000. Mycorrhizal fungi have a potential role in soil carbon storage under elevated CO_2 and nitrogen deposition. *New Phytologist* 147: 189–-200.