Modeling Settlement Patterns of the Late Classic Maya Civilization with Bayesian Methods and Geographic Information Systems

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Modeling Settlement Patterns of the Late Classic Maya Civilization with Bayesian Methods and Geographic Information Systems

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The ancient Maya occupied tropical lowland Mesoamerica and farmed successfully to support an elaborate settlement pattern that developed over many centuries. There has been debate as to the foundation of the settlement patterns. We show that Maya settlement locations were strongly influenced by environmental factors, primarily topographic slope, soil fertility, and soil drainage properties. Maps of these characteristics were created at the local scale and combined using Bayesian weights-of-evidence methods to develop probabilistic maps of settlement distributions based on the known, but incomplete, distribution of Maya archaeological sites, both domestic and monumental. The predictive model was validated with independently collected point-sampled field data for both presence and absence, predicting 82 percent of undiscovered Maya sites and 94 percent of site absence. This information should be of use in conservation planning for the region, which is under threat from contemporary agricultural expansion. Key Words: Maya settlement, predictive modeling, weights-of-evidence.

When the ancient Maya civilization was at its height in the Late Classic, from about AD 600–900, a vast and complex system of centers developed that included a tiered urban hierarchy of major and minor centers, household farms, and remote buildings spread across the landscape. Populations of the southern Yucatan Peninsula—the greater Petén surrounding northeastern Guatemala typifying the Maya forest (The Nature Conservancy 2007)—have been estimated to be as high as nine times that of today. Currently, only a small fraction of the Maya settlements have been discovered, mapped, and analyzed. Given this incomplete record, our research applied methods that use the integrative power of geographic information systems (GIS) and Bayesian statistical modeling to predict the probable spatial distribution and

Los antiguos mayas ocuparon las tierras bajas tropicales de Mesoamérica y produjeron una agricultura tan exitosa como para sostener un elaborado patrón de poblamiento, desarrollado a lo largo de varios siglos. Se ha presentado debate en lo que concierne a la fundación de los patrones de aquel asentamiento. Nosotros mostramos que las localizaciones de los asentamientos maya fueron fuertemente influenciadas por factores ambientales, en especial la pendiente topográfica, la fertilidad del suelo y las propiedades del drenaje de los suelos. Para representar estas características, se crearon mapas a escala local, combinándolos con el uso de métodos bayesianos de peso-de-evidencia a fin de desarrollar mapas probabilísticos de la distribución de los asentamientos. Se tomó en cuenta la conocida aunque incompleta distribución de los sitios arqueológicos maya, tanto domésticos como monumentales. El modelo predictivo fue validado con datos de campo independientemente obtenidos en puntos de muestreo para presencia y ausencia, pronosticándolo el 82 por ciento de sitios maya sin descubrir y el 94 por ciento de ausencia de sitio. Esta información debería ser utilizada para planificar la conservación de la región, que se halla bajo la amenaza contemporánea de la expansión agrícola. Palabras clave: asentamientos mayas, modelación predictiva, peso-de-evidencia.
number of Maya settlements from the subset of known sites. The purposes of the modeling were to (1) assess the influence of environmental constraints on ancient Late Classic period Maya settlement and agriculture, (2) permit tests of the validity of the Maya settlement model in the field, (3) allow the existing estimates of Maya population size and density to be assessed, and (4) propose a map showing those lands with both undisturbed forest and numerous Maya settlements that have the most to gain by conservation. Importantly, we offer the first strong quantitative and spatial method for linking ancient Maya settlement patterns to ancient agricultural patterns.

As an agrarian society, it is well documented that the development of the ancient Maya transformed the region known to conservationists as the Maya forest into a sustained and sustainable human landscape for millennia. Although the development of the ancient Maya is well researched, there remains debate over the complexity of their subsistence adaptation and patterns of settlement distribution. The largest centers, such as Tikal, arose in areas where no agro-engineering feats have been identified, implying a constellation of complex labor-intensive land use strategies that have left no trace (cf. Nations and Nigh 1980; Nigh 2008). The dense forest environment encountered today has shrouded the archaeological view of the Maya landscape, one of the few ancient civilizations that emerged in the now densely vegetated tropics (Bacus and Lucero 1999). The incomplete data on settlement distribution, civic center locations, and land use stimulate debate on ancient Maya population (e.g., Rice 1978; Turner 1990; Ford 1991b). In most cases, scholarship has ignored the quantitative relationship between the spatial distribution of Maya settlements and its patterned interaction with the environment that controlled aspects of everyday life. In this study, the significance of geographic resources to the Maya settlement and land use patterns are considered for the culminating period of the Late Classic when the ancient Maya civilization was at its apex and nearly all habitation sites were occupied (Culbert and Rice 1990). We use the data fusion capabilities of GIS with data from the recently developed University of California at Santa Barbara (UCSB) Maya Forest GIS (ADL 2004). Using these data, we applied weights-of-evidence Bayesian statistical techniques to explore the unknown components of the settlement patterns as a supplement to those known to archaeology.

There is a substantial body of research and data on Maya settlement and interpretations of patterns based on surveys in sample areas of the region (e.g., Bullard 1960; Ashmore 1981; Fedick and Ford 1990). These studies show that environmental factors played a role in Maya site location, but the spatial implications of these arguments have not been fully pursued. It is generally acknowledged that settlement densities were high and that distributions should be related to agriculture (Fedick and Ford 1990), suggesting a wide diversity in agricultural pursuits (see Whitmore and Turner 2001). These settlement data are used as a proxy for population (Culbert and Rice 1990) and, by extension, land use.

Population estimates for the ancient Maya are most often a starting point for discussions of land use and agriculture (e.g., Dahlin et al. 2005), with ranges from 100 to 1,000 persons per square kilometer or more, much greater than existing densities in the same area. Major centers, such as Calakmul, Tikal, and Caracol, have proposed densities of 1,000 to 2,000 people per square kilometer (Culbert and Rice 1990), equivalent to contemporary Sri Lanka. These estimated population figures are incompatible with other aspects related to the steady expansion and development of the Maya in prehistory (Turner 1978). Yet without a spatially distributed context for the Maya population, it is difficult to validate the estimates (Turner 1990, 178–211). A better understanding of the dimensions of settlement patterns is required to understand settlement distribution and land use. This is the objective of our research.

The archaeological record is, of course, incomplete. There are a number of reasons for this, but foremost among them in the Maya context are (1) the difficulty of exploring the mostly forested and isolated parts of the region; (2) archaeology’s bias toward research on the largest settlements; (3) the incomplete record of the entire settlement context from peripheral farmstead, household, and village to urban settings; (4) the variable nature of settlement data collection in the region; (5) the lesser likelihood of survival of smaller settlements, and (6) the difficulty in surveying a geographically significant bounded unit such as a drainage basin. Given these constraints, how can we interpolate the unknown Maya sites, both residential and civic, based on the recorded partial record? One way to accomplish this is with probabilistic spatial modeling. We chose to test a predictive model of the patterns of Maya settlement using the GIS at a local geographic scale of 1:50,000. At this scale, we focus on field data collection in the El Pilar area in the vicinity of Belize River (Figure 1). The weights-of-evidence method was used to convert maps for the area into probabilities of settlement using the known point distributions of archeological sites from the El Pilar area (Ford 1990, 1991a, 1992, 1993; Ford...
and Fedick 1992). New field data were collected to validate the model. The results impact our understanding of Maya land use in the past and resource management for the future.

The Geography of the Maya Forest

The Maya forest region, as defined by conservationists (The Nature Conservancy 2007), includes the tropical lowland setting of the greater Yucatan Peninsula including parts of eastern Mexico, northern Guatemala, and Belize (Figure 1). The region was densely occupied in prehistory. Today, it is characterized by rolling limestone hills and ridges (Turner 1978), most covered by a deciduous hardwood forest. This verdant growth thrives on an annual rainfall average of 1,000 to 3,000 mm that falls mainly from June to January. A dry season runs from January to June. Activities today are seasonal, impacted by this wet–dry deluge and drought sequence, as they were in the Maya prehistory (Haberland 1983; Ford 1986, 1996; Scarborough 1998; Lucero 2002; Peterson and Haug 2005; see also Ewell and Sands 1987). The Maya forest, a biodiversity hotspot, consists of large protected areas (Nations 2006), but population expansion and associated farming as well as commercial agricultural and cattle pastureage are pushing the development frontier into the contiguous forest areas. Until recently, 85 percent (30,000 km²) of the Petén of Guatemala was covered with semideciduous subtropical moist forest. Less than 50 percent now remains (Sader et al. 2004).

Land clearing often reveals the location of archeological sites and leads to their destruction by erosion, looting, and plowing. With the long-standing interest in the Maya, the impact of tourism has been slight, but larger sites with monumental architecture are often developed for tourism and some rank among the greatest existing windows into the ancient Maya world. Mapping of smaller ancient sites, although incomplete, varies by country. Current trends to move to digital coverage have produced a surprising amount of GIS data that can be gathered from existing sources and mapping agencies in Belize, Guatemala, and Mexico. Despite the spotty nature of the accessible settlement data in the Maya area, it is clear that, at the height of the ancient Maya during the Late Classic, the number of inhabitants of the region as a whole was significantly greater than that of today, with little difference in geographic resources. The general climate regime has retained its wet–dry annual cycle within the context of a general drying trend over the past 4,000 years (Deevey et al. 1979; Hodell, Curtis, and Brenner 1995; Curtis, Hodell, and Brenner 1996; Haug et al. 2001). It is also evident that, despite the blanket population densities, settlement and land use patterns were far from uniform over the landscape (e.g., Turner 1978; Fedick and Ford 1990).

The ancient settlement distribution in the Maya forest relates to a complex mosaic of regional land resources (Fedick 1996; Ford 1986). Settlement densities are recorded as the highest in the well-drained hills of the region (Bullard 1960; Puleston 1973; Rice 1976; Rice and Puleston 1981; Fedick 1989; Fedick and Ford 1990). For the El Pilar Study area, 98 percent of the residential sites tested dated to the Late Classic period (Ford 1992; Fedick and Ford 1990). This is the period when the land use was at its greatest and the overwhelming majority of sites were occupied (Culbert and Rice 1990). The Late Classic is the period that we considered in our modeling of ancient Maya settlement.

The limestone ridge lands are concentrated in the central areas of the Maya forest (Turner 1978). The area is characterized by shallow and fertile Molisols (also known as Rendzinas; Food and Agriculture Organization of the United Nations [FAO] 2008) of excellent quality (Fedick 1988, 1989), representing between 1 and 2 percent of the world’s tropics, yet nearly 50 percent of the soil around the ancient Maya city of Tikal (Fedick and Ford 1990; see also Kellman...
Evidence indicates that the interior Petén area around Tikal can be traced back 5,000 years (see Leyden et al. 1993; Curtis, Hodell, and Brenner 1996; Islebe et al. 1996; Curtis et al. 1998; Hodell, Brenner, and Curtis 2000; Brenner et al. 2002; Rosenmeier et al. 2002), this endurance reflects a flexible adaptation and robust strategies that bridged periods of disturbance and extremes, such as hurricanes and drought.

Despite the evidence that the Maya forest environment did support high settlement densities in the past based on a sustained land use strategy, little effort has been made to identify the balance that was attained by the ancient Maya land use pattern. Instead, modern industrial strategies are proposed for development that bear no resemblance to the past (for the Belize River area, see Birchall and Jenkin 1979) and can be seen as a destructive short-term trajectory in process (Turner 1990; Sever 1999; Sever and Irwin 2003; Nations 2006). By identifying the spatial land use priorities of the ancient Maya, we can assess the contrast of development planning used in the region. The success of the past strategies, the needs of contemporary local populations, and the conservation demands of the twenty-first century underscore the imperative to understand the basis of the past prosperity and sustainability of Maya agriculture.

To what extent does the fundamental geographic setting of the ancient Maya civilization account for its collapse (e.g., Culbert 1973, 1988; Redman 1999; Diamond 2005) and the search for the causes of the collapse has generated a substantial literature (see Webster 2002). Whatever the cause of the abandonment of the great Classic Maya cities, the development of Maya social complexity was based on a gradual rise in population and concomitant intensification of land use, including farming of increasingly more difficult and marginal land (Fedick 1992).

Early investments and development in the Maya forest landscape endured over time (see Whitmore and Turner 2001, 111) and the ancient Maya civilization integrated populations of the region over a span of more than 2,000 years. Environmental dimensions offered attractions as well as constraints for the early ancestral Maya. Among these attractions is soil fertility constrained by the critical problem of surface water (Ford 1996). Subsistence strategies and cultural developments mediated constraints and agricultural diversity sustained the steady growth of the Maya civilization (Whitmore and Turner 2001, 100–107). Given the fine scale evidence for precipitation variation over this long period (Haug et al. 2001) coupled with the extensive studies of the Petén lakes (Leyden et al. 1993; Curtis, Hodell, and Brenner 1996; Islebe et al. 1996; Curtis et al. 1998; Hodell, Brenner, and Curtis 2000; Brenner et al. 2002; Rosenmeier et al. 2002), this endurance reflects a flexible adaptation and robust strategies that bridged periods of disturbance and extremes, such as hurricanes and drought.

Scholars have focused on the dramatic Classic Maya collapse (e.g., Culbert 1973, 1988; Redman 1999; Diamond 2005) and the search for the causes of the collapse has generated a substantial literature (see Webster 2002). Whatever the cause of the abandonment of the great Classic Maya cities, the development of Maya social complexity was based on a gradual rise in population and concomitant intensification of land use, including farming of increasingly more difficult and marginal land (Fedick 1992).

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adaptation? Our research focuses on geographic data as a means to isolate the subsistence economy from the political and social factors. We use geographic variables that directly influence agriculture, past and present (Jenkin et al. 1976; Birchall and Jenkin 1979), and include field improved digitized 1:50,000 maps of the soils (based on Fedick 1988, 1989, 1994). We focus on settlement patterns of the Late Classic period, the apogee of the Maya civilization, representing the accumulation of two millennia of Maya accomplishment.

Weights-of-Evidence Analysis

The premise of our model is that an actual map of ancient Maya sites and settlement distribution consists of a set of all locations, including the subsets of locations that remain unknown and locations of known archeological settlements. The actual distribution cannot be known but can be modeled probabilistically, and by focusing on strictly geographic variables we avoid basic weaknesses of proxies identified in earlier predictive models (see Kohler and Parker 1986). The settlement distribution is assumed to spatially reflect mapped distributions of major geographic and environmental factors. Among these are topographic slope, soil fertility, soil drainage, and proximity to water sources. These factors each contribute independently to the location of all settlements, but in different degrees. These amounts, or weights, are the basis for the use of weights-of-evidence (Monts-Homkey 2000; Ford and Clarke 2001; Raines, Bonham-Carter, and Kemp 2000; Sirjean 2003; Monthus 2004). Weights-of-evidence origins are in mining geology (Bonham-Carter 1999). The essential tools were integrated into a GIS software package, ESRI’s ArcView 3.2 and later ArcGIS (Sawatzky et al. 2004), and extended into a broader analysis package called ArcSDM.

Weights-of-evidence methods are Bayesian methods. They involve a given point distribution, assumed to be a sample or incomplete representation of a spatial distribution that is the consequence of the combined influence of multiple influential factors or themes, represented as binary or categorical maps. The thematic maps are usually reduced category sets, or classified fields, processed by buffers or other map-based transformations. The influences can be positive or negative (i.e., a map class is prohibitive to the sample rather than causative) but must be independent of each other. These thematic maps, when overlain with the point sample, result in an expected statistical density for each class. The explanatory significance is compared to random variation; that is, does a particular class increase or decrease the likelihood of finding a positive sample by a significant amount. Each map contributes explanatory power to the point distribution proportionally (the weight). By assembling the sum of the weighted contributing factors as a map overlay, a probabilistic surface representing the likely complete distribution density can be generated and used in modeling, simulation, and forecasting.

Weights-of-evidence analysis follows six steps:

1. Select known points of features to be modeled, such as Maya sites.
2. Select thematic maps that are suspected to contribute to the explanation of the point distribution.
3. Using the correlation analysis tools of weights-of-evidence, convert selected map layers to binary or categorical form in the most predictive manner.
4. Test for conditional independence comparing prior and posterior probabilities by class combinations, eliminating those maps that do not contribute explanatory power.
5. Create a set of weights to use for each layer using Bayesian methods.
6. Develop posterior probability and the associated uncertainty maps using the weighted layers (Bonham-Carter 1994; Raines 1999).

Any model is, of course, only as good as its ability (1) to be calibrated and validated to reflect past and existing data; (2) to summarize and simplify a real system to allow experiments and test hypotheses; (3) to allow aggregate investigations that would not be possible by testing parts in isolation; and (4) to be transportable across scales or regions. The weights-of-evidence model allowed us to forecast where to expect and not expect Maya settlements, promoting an independent means of validation. The model also allows us to see the relative importance of environmental factors in Maya settlement location choices. The probabilities can then be used as environmental weights in a settlement simulation. Although the actual application is not directly transportable, because the weights are derived for each case empirically, the approach is applicable universally and the posterior probability layer can be input into further models.

Each input map is converted into two or more categories based on the data. Of the detailed 1:50,000 soil classes on the UK Overseas Development Administration (ODA) survey of the Belize Valley (Jenkin et al. 1976), we condensed characteristics of soil drainage and
natural_text
area (Ford 1992). The ridge lands are the concentration of the settlements and the location of the largest Maya center in the area, El Pilar, situated 10 km from the Belize River (Ford and Fedick 1992, 45). The El Pilar study area includes only a minor presence of closed-depression wetlands, generally a significant component of the landscape of the entire Maya area (Fedick and Ford 1990; Dunning et al. 2002).

The landscape of the El Pilar area features the Belize River, one of the few rivers that run east from the central Petén. Rivers, and for that matter any surface watercourses, are scarce in the Maya region (Scarborough and Gallopin 1991; Scarborough 1994, 1998; Ford 1996; Lucero 2002). This makes the examination of the El Pilar area important. The alluvium of the El Pilar area, including the settlement of Barton Ramie (Willey et al. 1965), is notably fertile, yet makes up less than 5 percent of the study area (Fedick 1988, 1989; Fedick and Ford 1990; Ford 1992). Although likely a critical component of the earliest agricultural adaptations (Powis et al. 1999; Lohse, Awe, and Griffith 2006), the imposed growth limits are evident given the later periods of occupation that concentrate in the abundant ridge lands north and into the interior. The valley provides a very restricted area for expansion and development; consequently, it does not constitute a major focus of Late Classic Maya occupation (Ford 2006).

The importance of water cannot be overemphasized (Scarborough 1994; Ford 1996). Unchecked, surface water is quickly absorbed into the limestone bedrock and follows invisible and inaccessible aqueducts within the limestone. Our examination of the El Pilar area will provide a means of identifying the priority of watercourses for Maya settlement patterns.

Regional examinations of major centers have suggested a number of underlying factors contributing to location. These include local and long-distance trade, political competition, and access to critical resources (Marcus 1973, 1993; Fry and Cox 1974; Rice 1981; Freidel 1986; Sabloff 1986; Ashmore 1991; Demarest 1992; Martin and Grube 1995, 2000; Fox et al. 1996; Foias and Bishop 1997). Patterns of spacing have been considered along with center size and site sustaining area (Marcus 1976). Our research examines geographic variables most useful from the agricultural perspective. Early agricultural occupations have been recognized as later settlement concentrations and ultimately the focus of Maya civic centers (Ford 1986; Fedick and Ford 1990). Thus, our predictive modeling targeted archaeological patterns as a whole, residential and civic, reflecting the agrarian foundations of the Maya. We considered all archaeological signatures, complex and simple residential units as well as major and minor monumental centers together, as seen in Table 1.

From the numerous data contained in the Maya Forest GIS (ADL 2006), a subset of our environmental data layers defined by the northern drainage catchment of the Belize River were extracted and clipped to the

<table>
<thead>
<tr>
<th>Theme</th>
<th>Scale and extent</th>
<th>Map source</th>
<th>Resolution</th>
<th>Classification</th>
<th>Transform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil fertility</td>
<td>El Pilar area</td>
<td>Digitized paper map (Jenkin et al. 1976)</td>
<td>1:50,000</td>
<td>4 classes</td>
<td>4 classes</td>
</tr>
<tr>
<td>Soil drainage capability</td>
<td>El Pilar area</td>
<td>Digitized paper map (Jenkin et al. 1976)</td>
<td>1:50,000</td>
<td>4 classes</td>
<td>4 classes</td>
</tr>
<tr>
<td>Topography</td>
<td>El Pilar area</td>
<td>Paper official topo 40 m</td>
<td>1:50,000</td>
<td>40 m contours</td>
<td>Slope percent (percent), below and above 16 percent</td>
</tr>
<tr>
<td>Rivers and streams</td>
<td>El Pilar area</td>
<td>Belize data</td>
<td>1:50,000</td>
<td>Perennial and intermittent streams</td>
<td>Distance buffers</td>
</tr>
<tr>
<td>Lakes and water bodies</td>
<td>El Pilar area</td>
<td>Paper official topo 40 m</td>
<td>1:50,000</td>
<td>All</td>
<td>Distance buffers</td>
</tr>
<tr>
<td>Archaeological sites</td>
<td>Site local</td>
<td>Belize River Archaeological Settlement Survey/El Pilar Institute of Archaeology</td>
<td>1:2000</td>
<td>Major or minor civic center/residential sites undifferentiated</td>
<td>1 class</td>
</tr>
</tbody>
</table>
extent of our study area (Figures 1 and 2). The subset and input layers were selected at the local scale and extent as listed in Table 1 and are shown by the outline polygon in the southwest of Figure 2. The study area is located between the Belize–Guatemala border and the Belize capital of Belmopan and focused on the north side of the river. The area extends from the western limestone ridges and hills to the eastern lowlands and wetlands. All data themes of the GIS were consistently registered to WGS84 using the Universal Transverse Mercator coordinate system in zone 16 North.

The weights-of-evidence module used here was an extension to ArcView 3.3 as an Avenue script utility that is introduced into ArcView as a regular extension and becomes an additional menu on the main ArcView software toolbar. The extension has been rewritten and extended and is now available as a more general analytical package and for other versions of the ESRI GIS software (ArcSDM; Sawatzky et al. 2004). Using the tool involves following the weights-of-evidence steps outlined earlier. The tool includes a means to experiment with layer combinations, layer independence, category aggregation, and statistical fitting of the model. After sorting and preprocessing statistical tests of different class breakdowns, we reduced the combinations to a workable set of four principal classes and themes: soil fertility, soil drainage, slope, and distance to watercourses.

The soil layers were based on the four described soil suites and subsuites in Birchall and Jenkin (1979) and

Figure 2. Location map for the application zone and validation zone showing the training samples from the Belize River Archaeological Settlement Survey and Global Positioning System field data site locations.
Table 2. Soil fertility ranking

<table>
<thead>
<tr>
<th>Fertility class</th>
<th>Cation exchange capacity</th>
<th>Base saturation</th>
<th>Phosphate</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High</td>
<td>High up 100%</td>
<td>Low</td>
<td>5.8–8.2</td>
</tr>
<tr>
<td>2</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>4.1–8.2</td>
</tr>
<tr>
<td>3</td>
<td>Moderate to high</td>
<td>Moderate to high</td>
<td>Low</td>
<td>4.2–8.3</td>
</tr>
<tr>
<td>4</td>
<td>Variable</td>
<td>Variable</td>
<td>Low</td>
<td>3.5–7.6</td>
</tr>
</tbody>
</table>

are detailed in Fedick (1988, 179–202). The suites are based on landforms and the subsites based on location. The locations include alluvial parent material in river valleys with young, mature, and poorly drained soil; limestone on the ridges, escarpments, and plains that vary based on parent location; Pleistocene coastal deposits primarily of sand and clay; and wetland areas flooded in the rainy season based on limestone or acid rocks (Birchall and Jenkin 1979, 13).

According to the field results of Birchall and Jenkin (1979) and Fedick (1988), we ranked soil fertility from 1 (fertile) to 4 (infertile). Soil fertility rank is based on cation exchange capacities (CEC), base saturations (Ca\(^{2+}\), Mg\(^{2+}\), K\(^{+}\), and Na\(^{+}\)), along with phosphate and pH levels as identified in Birchall and Jenkin (1979) and employed by Fedick (1988, 1989). We summarize the fertility classification in Table 2.

Based on the analysis of Birchall and Jenkin (1979) coupled with the field survey of Fedick (1988, 1989), we were able to classify drainage characteristics of the soil. We ranked drainage from 1 (good) to 4 (poor). Soil permeability, infiltration, and clay content form the basis of our ranking, summarized in Table 3.

The themes of slope and watercourses were defined based on the 1:50,000 scale maps digitized as GIS layers as well as the Shuttle Radar Topographic Mapping (SRTM) data. We defined slope in percentages. In considering access to water, based on statistical tests, we explicitly eliminated as explanatory variables distance to the major river, distance to lakes, and distance structured by Horton stream order. Watercourses were thus defined as any perennial stream or river.

Our set of four principal classes and themes of soil fertility, soil drainage, slope, and distance to watercourses were included in this study as the evidential layer inputs for investigating the geographic conditions of Maya settlement (Figure 3). They are as follows:

- **Theme 1: Soil fertility.** Classes: good, moderate, poor, very poor.
- **Theme 2: Soil drainage.** Classes: good, moderate, poor, very poor.
- **Theme 3: Slope (percentage).** Classes: integer percent, reduced to above and below 16 percent.
- **Theme 4: Distance to watercourses (meters).** Classes: integer meters, tested in 100 m bands, reduced to 0 to 500 m, 500 to 1,000 m, and greater than 1,000 m.

The choice of weights-of-evidence model weights was based on the statistics, especially the number of points explained by the weighted combination. The grid size for the model was one hectare, with an area of application of 83.59 km\(^2\) in the local case. The archaeological sites layer included 262 sites in the evidential theme. The analysis was repeated, first with the application zone surrounding El Pilar and next with the validation zone for the entire El Pilar/Belize River area of 1,290.11 km\(^2\), constituting a major portion of western Belize. The relationships between the two areas are shown in Figure 2 and 3. This formed the basis of our analyses.

### Analyses and Results: Predicting Ancient Maya Settlement

The predictive modeling of ancient Maya settlement patterns focused on the archaeological survey data of the BRASS/El Pilar surveys, the source of the training sites for the predictive model (Ford 1991b, 1992). The locations of the training sites were based on 1:2,000 scale composite maps of archaeological sites, residential and civic (Ford and Fedick 1992). The modeling exercise was divided into the two phases. First, we used existing data from the surveys to define the application zone (83.59 km\(^2\)) and developed the initial model. Second, we expanded the initial model from the application zone to the validation zone (1,290.11 km\(^2\)) and field corroboration. This phased examination provided the basis of our model development and the field tests.
The application zone for the El Pilar area was grid-
ded by the software at 100 m resolution (one-hectare
cells). For the 262 surveyed archaeological training sites
(predominantly residential and including civic centers;
see Table 1 and Figure 2), the expected a priori proba-
bility of encountering a site in a cell was calculated as
0.0313. As defined in Table 4, contrast indicates that
soil fertility has the strongest spatial correlation with
training sites, followed by proximity to watercourses.
Soil drainage and slope are approximately equal factors,
both of less importance than soil fertility and proximity
to watercourses.

Table 5 shows the criteria used to select the evidence
layers and the thresholds defined by the weights anal-
ysis. Soil fertility and drainage are ordered data, each
with four ranks. In both cases the highest ranks were
defined as the optimal predictor of training sites. Slope,
an ordered measure of slope angle, was analyzed using
the cumulative ascending method to define a 16 per-
cent slope as the optimal maximum slope preferred by
the Maya, as indicated by the training sites. Slope has
the lowest confidence, where a value of 1.6316 would
indicate an approximate level of confidence of 95 per-
cent. This significance test is approximate, as it is based
on all of the data rather than a random sample.

In the first test of our model in the application zone,
197 sites were explained with the weighted evidence
model. Sixty-five of the 262 points had a posterior

Table 4. Weights table for the application zone

<table>
<thead>
<tr>
<th>Evidence</th>
<th>W1</th>
<th>W2</th>
<th>Contrast</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil fertility</td>
<td>0.6813</td>
<td>−0.9796</td>
<td>1.6609</td>
<td>11.2877</td>
</tr>
<tr>
<td>Watercourse proximity</td>
<td>0.6314</td>
<td>−0.4575</td>
<td>1.0889</td>
<td>8.7517</td>
</tr>
<tr>
<td>Soil drainage</td>
<td>0.6015</td>
<td>−0.2391</td>
<td>0.8407</td>
<td>6.5745</td>
</tr>
<tr>
<td>Slope</td>
<td>0.0193</td>
<td>−0.8032</td>
<td>0.8225</td>
<td>1.6316</td>
</tr>
</tbody>
</table>

Table 5. Criteria and thresholds for the chosen
weighting model

<table>
<thead>
<tr>
<th>Evidence</th>
<th>Criteria</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil fertility</td>
<td>Preferred high-fertility soils</td>
<td>Class = Good soil fertility</td>
</tr>
<tr>
<td>Watercourse proximity</td>
<td>Near to the river but not too close</td>
<td>500–1,000 m from river</td>
</tr>
<tr>
<td>Soil drainage</td>
<td>Preferred well-drained soils</td>
<td>Class = Good soil drainage</td>
</tr>
<tr>
<td>Slope</td>
<td>Preferred low slopes</td>
<td>Less than or equal to 16°</td>
</tr>
</tbody>
</table>
probability less than the prior probability and therefore were not explained by the weighted evidence model, resulting in a 75.2 percent overall explanatory level. Of these sixty-five unexplained points, forty fell in the first slope class (0–9 percent) and grouped in clusters at the south of the BRASS survey transect near the minor center Yaxox, in the preferred watercourses Class 2; that is, within 100 to 500 m of a watercourse.

The analysis of the proximity to watercourses is particularly interesting, as the data show that the Maya preferred to live close to, but not too near, watercourses (Table 6). This might have been to avoid areas of flooding along the rivers and streams, as is supported by field observations, and with a consistent avoidance of wetlands. The actual buffer interval was defined by using a categorical weights table. Note that the weights are well defined because the distance intervals are large. In analyses with narrower distance intervals, the selected interval was mostly of positive contrast, but there were occasional negative contrasts inside the interval (Sirjean 2003). This is a consequence of the sample size of the training set. This particular evidential layer and its analysis represent a unique contribution of this research project and are potentially useful for others working with weights-of-evidence. Rarely is a single influential theme both a positive and negative contributor to the explanation of a distribution (Table 6), with distance forming the key variable.

All evidence was generalized within the context of the weights-of-evidence to optimize prediction into binary classes (i.e., predictive or nonpredictive), by selecting the maximum contrast that had a confidence level of 90 percent or greater based on an approximate Student’s t test. The soil fertility, soil drainage, and slope were all analyzed by the appropriate cumulative weights measurement to define the threshold for good and bad evidence as summarized in Table 5. Slope weights analysis was done using the cumulative ascending method because the question asked of the data was this: What was the maximum low slope preferred by the Maya farming settlements? Soil fertility and drainage were appropriately analyzed by cumulative ascending because the ordered ranks were numbered with one as the highest rank. This ordered numbering sequence dictates using cumulative ascending weights analysis to answer the question of how good of a soil would the Maya farmer use. The answer for both fertility and drainage was Class 1, or good. The proximity to watercourses weights analysis was done using a unique categorical weights analysis supported by testing the reclassification of the evidence with categorical weights (results are shown in Table 6).

Conditional independence is always an issue when using a Bayesian method such as weights-of-evidence. The rule is to accept a conditional independence value greater than 0.85. In our test, the overall conditional independence test reported a value of 0.97. This overall test is considered conservative, and thus there is no conditional independence problem in our model. The chi-square pairwise test indicates a weak conditional dependence between soil fertility and soil drainage and between soil fertility and proximity to watercourses. The overall test, however, indicates no significant problem of conditional independence. These conditional dependencies are reasonable because fertility and drainage and the favorable linear buffered region around the watercourses are probably moderately associated. These considerations, however, do not change the model because the intended use of the model is to rank areas.

Our results in the application area are supportive. We were able to predict 75 percent of the sites based on the combined environmental inputs. The next step was to perform the field tests of the model.

### Validation of the Predictive Model of Maya Sites

Field validation tests expanded the results of the El Pilar application zone to the entire Belize River validation area (Figure 4). The continuous weights were classified into four categories (very high, high, low, very low) and applied to the validation area. The exercise to confirm the predictive model of ancient Maya sites focused on specific zones of interest based on the topography and the model results themselves. Three zones
were defined for the field validations. Zone One represents areas comparable to those of the BRASS/El Pilar surveys with a similar geography. Zone Two is located south of the BRASS/El Pilar surveys in the area between the Mopan and Macal River branches of the Belize River. The last zone, Zone Three, was focused on the valley north of Barton Ramie, where the predictive model shows serpentine shapes of contrasting poor and moderate prediction for Late Classic archaeological sites (see Figure 4), similar to the location of the area of unexplained sites of our model in the application zone.

Each validation zone was visited, canvassed, and surveyed in the field. We located areas within each zone for the validation tests by vehicle. Once oriented, the selected area was covered by foot. Sites were recorded with ESRI’s ArcPad running on a Compaq iPAQ with a NAVMAN Global Positioning System (GPS) sleeve, while displaying the weights layer in the GIS. These data were then compared with the model and evaluated in terms of reliability.

The first validation zone was focused on the northwestern area of the model, north of El Pilar around Cadena Creek. This zone is very similar to the geography around the major center of El Pilar. Today, Zone One is largely in plough and pasture with good access by all-weather roads maintained by the Mennonite community of Spanish Lookout. Concentrating on the places with the strongest predictability for sites, we plotted the unmapped Maya residential sites and minor centers encountered in the many cleared fields. Predictably, a high density of sites characterized the locales with high probability weights. Most ancient Maya residential sites were found within 20 to 30 m of each other. Several minor centers were identified as well. This density of sites in this zone is typical of the densely settled areas of the Maya lowlands and leads one to imagine an intense occupation of these high-probability areas. Other probability areas were canvassed as well, and all sites were recorded.

In total, we identified 225 sites in Zone One, all previously unmapped. Of the total, 122 of the sites, or 54.2 percent, were recorded in the areas of very high probability and a further 55 or 24.4 percent in the high-probability area. Sites were also located in the lower probability areas: 35 or 15.5 percent in the low-probability areas and 13 or 5.7 percent in very low-probability areas. Most of the sites in these low-probability areas are near areas of high probability, suggesting some imprecision or generalization of edge locations in the evidential themes. Considering together areas of very high and high probability, recorded sites account for 76.8 percent of all sites of the validation test. The model proved reliable in this zone.
The second validation zone we examined was the area south of the El Pilar area between the Mopan and Macal Rivers. Zone Two is marked by difficult broken terrain and steep hills that are not well reflected in the digital elevation model (DEM) for the region. Nevertheless, eighty-one new sites were located, of which seventy-four were in the high-probability areas, accounting for 91.3 percent of the documented sites in this zone. The remaining seven sites, or 8.6 percent, were located in the low-probability areas. The model predicted correctly all the locations of newly identified sites. In addition, the high-probability areas correspond to those mapped in the area of the Chan site (Robin 2002). In this area no sites fell in the very low-probability area.

The third validation zone we considered was east of the El Pilar area bordered by the Belize River where the first archaeological surveys of the area were conducted around Barton Ramie (Willey et al. 1965). This is where the model shows serpentine areas of low probability next to areas of high probability based on watercourses. This model pattern comes from the relationship of sites to watercourses, where the majority of site locations fall between 500 and 1,000 m from a watercourse (see Table 6). Yet in the case of Zone Three, both areas have poor soils, generally a poor predictor of site locations. Only three sites were found in the vast expanses of Zone Three. Of these sites, one was in the high-probability area (33.3 percent), one was in the low-probability area (33.3 percent), and one was in the very low-probability area (33.3 percent). None were located in very high-probability areas.

Although there are very few sites in Zone Three, they are evenly divided among the high-, low-, and very low-probability classes. Only one site, or 33.3 percent, was located in a high probability area, and two, or 66.6 percent, were located in low-probability areas, suggesting some uncertainty in the predictability in this very lightly settled zone. All the sites were situated on the margins of the defined zone. The one site in the high-probability area was located 13 km north of the river near limestone ridges know as Yalbac Hills. The other two were located close to the Belize River. These results suggest that work on the precise nature of the influence of drainage and Maya site location still needs to be addressed. Nevertheless, barely 1 percent of the all the newly recorded validation sites were identified in the large expanse of Zone Three.

In conclusion, the predictive model of ancient Maya sites held up well to the field validation tests. We located and recorded 315 sites in the validation tests and 82 percent of these sites fell in the very high and high-probability areas as mapped by the weights-of-evidence model. These newly recorded sites were divided relatively evenly between probability areas: very high with 39 percent and high with 43 percent (Table 7). The very high-probability areas are densely settled; there were 122 recorded sites in only 5.6 percent of the study’s areal extent. The high-probability areas were more spread out and included 136 sites recorded in 19 percent of the study area (Table 7). Together these 258 new sites, accounting for four fifths of all validation sites, were predicted for only 24.6 percent of the study extent. The remaining 18 percent of the sites were distributed in areas of low and very low probability. Only forty-three sites (14 percent) were recorded in the area of low probability, and only fourteen sites (5 percent) were located in the very low-probability areas. Sites in the low-probability areas were distributed across 32 percent of the study, yet the few sites in very low-probability areas cover nearly 43 percent of the study extent (see Table 7). Thus, our model could exclude 42.7 percent of the study area based on geographic predictors with 96 percent confidence that no sites would be found.

It must be borne in mind that these figures reflect the uncertainty of the data collection and assimilation,

<table>
<thead>
<tr>
<th>Posterior probability</th>
<th>Percent masked area in class</th>
<th>Number of validation points (newly mapped sites) in region</th>
<th>Percent predicted sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1: 0.1039 to 0.225 black</td>
<td>5.55</td>
<td>122</td>
<td>39</td>
</tr>
<tr>
<td>Class 2: 0.0314 to 0.1039 dark gray</td>
<td>19.09</td>
<td>136</td>
<td>43</td>
</tr>
<tr>
<td>Class 3: 0.0087 to 0.00313 light gray</td>
<td>32.63</td>
<td>43</td>
<td>14</td>
</tr>
<tr>
<td>Class 4: 0.0 to 0.0086 white</td>
<td>42.74</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>315</td>
<td>100</td>
</tr>
</tbody>
</table>
Implications

The combined geographic themes were selected for their reflection of agricultural factors in the choice of site locations. In our research, we confirmed the conditional independence of the geographic variables with regards to the training sites, critical to the overall tests. The geographic themes were each contributors to the model and the combined themes of the predictive model can account for the majority of sites based on the validation field tests. The strong influence of soil fertility among the four themes is particularly relevant, supporting the view that agricultural strategies were at the foundation of Maya settlement patterns and development. Watercourses were relatively important, but more significant was that distances were found to be neither very close nor too far. Drainage and slope also played roles, ranked below fertility.

Our investigation of the predictive model for ancient Maya sites provides a means to evaluate land use patterns of the Late Classic Maya. Consistently, the results of our model implicate geographic motives for site location. These choices match contemporary smallholder farming choices for residence locations and underscore the importance of farmer choice in the selection of residential site locations. These locations would be the natural focus for the development of civic centers that would have responded to established settlement areas.

In this examination, sites have been predicted based on geographic variables and highlight the value of geography in explaining site locations. Although the agricultural basis of Maya settlement patterns has been appreciated, the spatial relationships had not been rigorously explored until now. Of particular importance here is the power of GIS to synthesize and coregister maps, supporting the analytical results and their validation in the field. Consequently, this examination brings to the fore the value of the weights-of-evidence method of evaluating multiple variables across space, demonstrating the combined contribution of geography and the value of agricultural choices to the settlement patterns of the ancient Maya.

With the weights-of-evidence method, we have isolated features of the geography in the Maya area that account for the majority of the archaeological sites, both residential and monumental. The areas of strongest probability of sites include only 24 percent of the entire validation area (see Table 7). As can be seen in the maps, these areas occur in scattered patches throughout the El Pilar area (Figures 4 and 5). In other words, 82 percent of the sites discovered in the validation tests (252) are found in dispersed high-probability areas without concentrating in any one particular area, such as adjacent to the Belize River or near the major center of El Pilar. This is noteworthy as the earliest surveys surmised that the Belize River exerted significant influence on Maya settlement (Willey et al. 1965).

The geographic preference for settlement in the limestone ridges is significant in that this geographic landform is a dominant characteristic of the entire Maya region from the El Pilar area west across the greater Petén of Guatemala and north to the modern state of the Yucatan, Mexico. The exploration of this modeling strategy for other study areas as well as the region as a whole might prove promising in identifying large-scale regional patterns of Maya land use. How much the
weights of the contributing factors vary with scale and region is a topic for future research.

The areas that evince the very lowest probability of sites include more than 42 percent of the El Pilar area (see Table 7) and yielded very few sites (fourteen, or 5 percent) in the field validation tests. Interestingly, these zones found in the El Pilar application area show both low density and small sites. Within the El Pilar surveys of the BRASS project, examples of such sites underscore the varied land use objectives of the Maya.

Examples of small sites in very low-probability areas around El Pilar were identified and tested in the BRASS survey (Ford 1990, 1991a, 1992; Ford and Fedick 1992). The sites are uniformly diminutive and excavations suggest that they were specialized in non-agricultural activities. Artifacts collected from excavations, for example, on the Yaxox transect (Figure 6),

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Figure 5. Examples of sites in high-probability areas from the application area, A: Latón, B: Alta Vista, and C: Bacab Na.

Figure 6. Examples of sites in very low-probability areas from the application area: Near the major center of El Pillar (left image) and north of the minor center Yaxox (right image).
indicate some of these were small-scale stone tool production sites that expanded in the Late Classic into the poorly drained lowlands adjacent to a chert quarry (Ford and Olson 1989); these areas were quickly abandoned in the Terminal Classic (Fedick 1989). A similar expansion pattern is noted for the very low-probability area adjacent to El Pilar (see Figure 6) where sites are recorded after the initial Preclassic, clearly related to the presence of El Pilar with its early construction dating to the Middle Preclassic (Ford 2004) and its growth and expansion thereafter. Thus, occupation in some of the lowest probability areas reflects other factors that might not relate to agriculture. Whereas sites around El Pilar may simply be infilling, the case of the Yaxox sites might be related to entrepreneurial economic specializations where resources, such as chert for stone tools or clay for ceramics, are found (cf. Brumfiel and Earle 1987).

Critically, our model demonstrates that ancient Maya populations that were living in the Late Classic period were not homogeneously distributed. There were specific areas that were preferred and general areas that were avoided for Maya settlement. The majority of sites were concentrated in the areas favorable to smallholder agriculture where fertility, watercourses, drainage, and slope supported farming. These features of the local geography are scattered, primarily based on parent geology, and occurred in less than one quarter of the study area (24 percent). An overwhelming majority of sites, 82 percent, were identified in these high-probability areas. This result has significant implications for the development of population estimates. If, as in the El Pilar case, the majority of sites that are used as proxy for population are concentrated in a small percentage of the land area, then projections of population need to be adjusted significantly downward and should exclude the majority of the landscape.

Although there are scholars who have clearly recognized the geographic preferences of the ancient Maya for the well-drained ridges (Turner 1978; Dunning 1996; Dunning et al. 1998), there are Maya scholars who project high population densities evenly across a region for the Late Classic Maya (Haviland 1969; A. F. Chase and Chase 1987; Dahlin et al. 2005; Healy et al. 2007; except Webster 2005). Our results, consistent with Turner and others (Turner 1978; Whitmore and Turner 2001), support the understanding of land use in developing population estimates (see also Turner 1990). In other words, part of the problem of understanding Maya land use comes from the way in which populations are estimated. Population estimates might be high in areas of settlement, but these are limited by geographic factors related largely to farming choices, as shown in our spatial model. The predictive model for the Maya sites of the El Pilar area provides a clear spatial view of the settlement and by extension population distribution. Not only should population densities be focused on areas that have a strong probability for occupation, but because these populations are largely agrarian in nature, these will tend to be the areas where agriculture would be practiced. Our predictive model provides the essential spatial criteria for making such assessments.

Translating our map results for the ancient Maya into land use and agricultural practice is an important step. To undertake this exercise, we first compare our predictive model to that of the Western model of contemporary development priorities. Given the prosperity apparent for the ancient Maya, how do the priorities of the predictive model for ancient Maya settlement compare with the contemporary development model? The answer to this is facilitated by the fine-scale and detailed soils research and agricultural undertaken in the Belize River area published in the 1970s (Jenkin et al. 1976; Birchall and Jenkin 1979). This agricultural assessment was undertaken within the context of a development scheme promoted by the United Kingdom and consistent with the United States for emerging economies since the last half of the twentieth century (Boserup 1965; Bray 1994; see also Fukuoka 1978; Mollison 1988; Nash 2007).

Following Fedick’s digitized classifications of these data and our field update and verification of the soil polygons, we evaluated the priorities of the UK ODA recommendations based on “suitability for arable use” (Birchall and Jenkin 1979, 5; Jenkin et al. 1976, 215), explicitly defined as geographic characteristics amenable to plowing (Jenkin et al. 1976, 215–16). With these data, we were able to compare the results of our model of ancient Maya settlement priorities based on Prehispanic Maya hand cultivation dependent on stone tools (Denevan 1992) and rainfed systems (see Whitmore and Turner 2001) to that of the contemporary development model based on mechanical cultivation dependent on technological systems.

To evaluate the relationship of the two models, we employed the attribute in the table of the 1:50,000 soil maps that ranked land capability class (Jenkin et al. 1976, 215–23). For the development model, we simplified the nine classes of the ODA study to four classes (1–4, high to low development priority) to compare
Table 8. El Pilar/Belize River area development class

<table>
<thead>
<tr>
<th>Development class</th>
<th>Percent area in class</th>
<th>Mean posterior probability, Set 1</th>
<th>Mean posterior probability, Set 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1: Black</td>
<td>5.8</td>
<td>0.0546</td>
<td>0.0578</td>
</tr>
<tr>
<td>Class 2: Dark gray</td>
<td>51.5</td>
<td>0.0014</td>
<td>0.0014</td>
</tr>
<tr>
<td>Class 3: Light gray</td>
<td>16.5</td>
<td>0.0418</td>
<td>0.0459</td>
</tr>
<tr>
<td>Class 4: White</td>
<td>23.2</td>
<td>0.0653</td>
<td>0.0671</td>
</tr>
</tbody>
</table>

with the Maya model (Table 8), based on the actual weights-of-evidence posterior probabilities (see Table 7). Two sets of random points were generated to populate each of the four development classes with one hundred points using Hawth’s tools (Spatial Ecology 2008). The total 400 points per set were intersected between class in the development model and posterior probability for the Maya model. The probability of finding a Maya settlement within each set of the four development classes was calculated based on the weights-of-evidence statistic and plotted for both sets of random numbers. The results of this test are presented in Figure 7 and Table 8.

Overall, the contemporary development classes show little in common with the Maya model. Excluding the top 6 percent of the potential development area, there is an inverse relationship with respect to the Maya model. The most dramatic distinctions come from the comparison of the lowest development class assigned for the limestone hills preferred by the Maya and the high development class assigned to the poorly drained lowlands virtually avoided by the Maya (see Figure 7).

Although the highest development priority areas, Class 1, proved a relatively good predictor of Maya sites (but hardly comparable to the weights-of-evidence) and shares some qualities in common with the Maya model, this class represents less than 6 percent of the study area and includes principally the restricted well-drained alluvial areas that offer value for hand and mechanical agriculture (Figure 8). Development Class 2 accounts for over 50 percent of the landscape of the study area with an assessed high potential for contemporary development, yet this high development class is the poorest predictor of Maya sites with mean weights-of-evidence probability in the very low-priority areas for the Maya (Table 7). Conversely, the lowest development priority (Class 4) is the best predictor of Maya sites, incorporating 23 percent of the study area largely located in the hilly terrain with thin soil (Figure 8). Thus, the contemporary development model that prioritizes based on arable land does not explain the ancient Maya land use strategies.

In considering alternatives to explain the Late Classic period Maya settlement model, Maya ethnographic and ethnohistorical data are important (Villa Rojas 1945; Redfield and Villa Rojas 1962; Hernández Xolocotzi, Bello Baltazar, and Levy Tacher 1995; Zetina-Gutiérrez and Faust 2006). These cases show that our predictive model shares much in common with the time-honored traditional practices of farmers

Figure 7. Comparison of the Maya model probabilities with the development model priorities.
in the Maya region today. The choices of soil, drainage, and slope characterize traditional land use techniques (Nations and Nigh 1980; Fedick 1995; Beach, Farrell, and Luzzadder-Beach 1998; Levasseur and Olivier 2000; Gómez Pompa et al. 2003; Levy Tacher, Rivera, and Rogelio 2005). Even the contemporary forest itself shows the signatures of ancient impacts with a plethora of economic plants (see Balick and Cox 1996; Balick, Nee, and Atha 2000; Campbell et al. 2006; Ford 2008; see also Balée 1994). Moreover, these high settlement density areas identified in the predictive Maya model exhibit considerable homogeneity of species indicated by high beta diversity (Campbell et al. 2006), reflecting a strong human impact of centuries of cultivation of tree-dominated plots despite current abandonment (see also Peters 2000).

Smallholders today who practice traditional farming strategies emphasize trees in their “forest gardens” and demonstrate the conservation of soil productivity, water retention, promotion of biodiversity, and support for birds and other animals (Gómez Pompa, Flores, and Sosa 1987; Gómez Pompa and Kaus 1990, 1999; Hernández Xolocotzi, Bello Baltazar, and Levy Tacher 1995; Griffith 2000; Ferguson et al. 2003; Ford 2008; see also Wilken 1987). In this way, our predictive model provides a basis for interpreting the ancient Maya site selection patterns (cf. Teran, Rasmussen, and Cauich 1998). The land use priorities identified in our predictive model maximize access to a combination of agricultural areas and vary the intensity of land use based on agricultural potentials across a wide sustaining area. The different land use strategies would be adapted to local productive capacities (Hernández Xolocotzi, Bello Baltazar, and Levy Tacher 1995), from polycultivated high-performance milpas (Wilken 1987) to shaded tree orchards with understory cover crops and productive palms as found in home gardens and outfields today (Gomez-Pompa and Vazquez Yáñez 1981; Corzo Marquez and Schwartz 2008). These differing levels of land use intensity would be reflected in the settlement size, composition, and density. Permanent residential units would be focused in the high productive areas, with seasonal and intermittent use of low productive areas, while avoiding the least productive areas for agricultural pursuits (see Zetina-Gutiérrez and Faust 2006; Zetina-Gutiérrez 2007). This is the infield–outfield model espoused by Netting (1977) and others.

In summary, we see the results of the predictive model of Late Classic Maya settlement as a critical basis for reexamining current themes of ancient Maya development and demise, for considering more diverse
subsistence adaptations, and for a reassessment of population levels. This first test at modeling ancient Maya settlement patterns has resulted in patterns that spread settlements and populations out into the mosaic of limited preferred zones of dense occupation of green communities (Voorhies 1982; Graham 1998), large areas with light occupation, and a proportion of the area with little or no evidence of occupation (see Fedick 1988). With these results we can begin to model land use and population levels that would best explain the patterns of the predictive model.

Further, the predictive model provides a foundation for examining the value of geographic variables at larger and smaller scales. Extending the model to the regional level for the whole lowland Maya area at, for example, 1:250,000, could provide insights into the variations of land use across the Yucatan Peninsula. We have recently developed a soil coverage theme for fertility and drainage of the entire Maya area (Sifuentes 2005). These new themes provide an opportunity to scrutinize the preference for farming sites in the region and to consider changes over time.

The results of our predictive model are promising, demonstrating that areas with Late Classic Maya settlement focused in environmental settings that support intensification of hand cultivation, avoiding areas that are difficult for these labor-based agricultural systems. The example from the El Pilar area reveals that the agricultural landscape is dispersed and fragmented, spreading the sites and populations out into large and small areas preferred for settlement and agriculture with no pattern of focus on rivers. Because the whole society was agrarian and dependent on the management of food production, our predictive model suggests that farming choices outweighed other factors in the development of the overall landscape. Wider testing of this model will help to better understand the diversity across the ancient Maya landscape.

Conclusion and Discussion

Late Classic Maya settlement distributions were arrived at over a long period of time. The patterns we have discovered are likely the product of adjustments to the overall characteristics of the landscape. From this study's perspective, however, it is not relevant whether the patterned results were deliberate or based on centuries of trial and error. Overall, what our results show is that four geographic and environmental factors predict 82 percent of the Maya sites in the high-probability areas. Furthermore, fully 96 percent of the settlement, a vast majority, can be predicted for less than 60 percent of the El Pilar study area.

Our conclusions are moderated by the uncertainties embedded in our data and in the assumptions of the Bayesian model. Given that the model is probabilistic, it might be difficult to use it for population density forecasts. A critical value is how many settlements are missing from the record. Exogenous estimates from cultural records or other sources could, nevertheless, be used with the model to simulate possible population distributions. Replication of this model in other local areas of the Maya lowlands would be important to build a broader database in support of our model. In addition, testing its validity at other scales, such as the greater region-wide scale, would provide another basis for interpreting land use and population distribution.

We propose that the probabilities computed for the model here can be used as surrogates or proxies for land use intensity and population distribution. Simple aggregation and integration would be sufficient to test the contemporary hypotheses about Maya population sizes and distributions. Thus, the foundation model developed here for the El Pilar area could shed light on Maya farming sustainability as well as the infamous Maya “collapse.”

Predictive models will become increasingly useful as more of the Maya archaeological record is destroyed. Although the likelihood of finding new major centers is not high, there must remain thousands of unmapped and unknown lesser centers, and certainly numerous farm and house sites that could be located with this tool, as our validation efforts have shown. Modeling geographic preferences could be a means of initial archaeological surveys for areas that have had little attention, such as the Lacandon forest of Chiapas, Mexico.

Given the broader implications, we believe that the use of GIS data with Bayesian methods offers value to predictive mapping of archaeology in the Maya forest. Additional factors, perhaps religious and political, not to mention economic, are likely to explain variation from the expected patterns, and better environmental data would improve the current example. Finally, we see a great potential of wider application of the model, perhaps to the whole Yucatan region, as well as to a narrower one at a major center such as El Pilar, among the next steps. Of most interest for such future tests is that the factor weights of the new models will show how environmental influences vary by geographical scale.
Acknowledgments

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Notes

1. The term Maya forest refers to the moist forest ecosystems of the lowland tropical parts of Maya culture area located between 15.45° N and 19° N latitude and 88° W and 91° W longitude at elevations below approximately 300 m (see also Whitmore and Turner 2001, 24, Table 2.1).

2. There has been considerable controversy on the subject of climatic change and the Maya area. Nonetheless, the general climatic regime is characterized as tropical with a wet–dry annual sequence that has continued over the recent Holocene period (Curtis et al. 1998; Hodell, Brenner, and Curtis 2000; Brenner et al. 2002; Rosenmeier et al. 2002; Neff et al. 2006). This period had included significant punctuated variations of deluge and drought, particularly in short-term precipitation changes that would have impacted the Maya (e.g., Haug et al. 2001; Peterson and Haug 2005).

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