Land, Water and Territory: A 3,000-year study of niche construction and cultural evolution in the Tikal National Park, Guatemala

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**CNH-Ex: Land, Water, and Territory: A 3,000-year Study of Niche Construction and Cultural Evolution in the Tikal National Park, Guatemala**

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**CERTIFICATION PAGE**

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Debarment and Suspension Certification

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* EAGER - Early-concept Grants for Exploratory Research

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Project Summary:
This project combines diachronic environmental simulation with historic settlement and environmental field survey to address a series of long-standing questions about the coupled natural and human history in the tropical lowlands of Central America, more specifically the Central Maya lowlands. The project investigates the relationships among land, water, population, settlement and political history for a three thousand year period using climate, soil and hydrologic modeling and time series spatial analysis of historic settlement patterns. The critical period we are studying (1000 BC to AD 2000) began with dispersed settlements associated with widespread deforestation and soil erosion. Population size and density grew rapidly for 800 years, while deforestation and erosion rates declined. This period was also characterized by striking evidence of political evolution, including monumental architecture, hieroglyphic monuments detailing wars and alliances, and the construction of an earthwork feature at our principal Maya center, Tikal, signaling a political boundary and possibly delineating natural resources (Webster et al 2007). Population decline and steady reforestation followed. The Penn State Integrated Hydrologic Modeling System (PIHMgis) and the Erosion Productivity Impact Calculator (EPIC) will be used to model the 3,000 year history of the Tikal National Park in Guatemala to compare land and water availability to the regional population and their consequences for political history. The project will analyze the spatial patterns of land and water availability under simulated conditions of drought, thereby addressing issues linking climate events and the cultural history of the Maya (primarily the famous “collapse” of the 8th-9th centuries).

This research contributes to understanding niche construction and inheritance, long-term environmental change, settlement patterns and critical issues facing smallholder agrarian communities throughout history. Additionally, this research will provide an enhanced understanding of one of the most compelling landscape narratives of coupled human and natural dimensions, i.e., the rise and fall of the ancient Maya in the lowland tropical forest of Central America. Importantly, the specific focus of our research a UNESCO world heritage site, located in the Maya Biosphere Reserve. The research approach integrates coupled climate, soil and hydrologic modeling, with archaeological approaches to settlement pattern research. The collaborative research team is highly interdisciplinary and includes anthropologists, a hydrologist, soil scientist, and a landscape archaeologist. Postgraduate, undergraduate and graduate students will be directly involved in the laboratory and field research activities.
In the 1960’s with the support of NSF funding (1967: GS-1409) William Haviland and Denis Puleston carried out an innovative research program to better understand and interpret the agricultural sustaining area of the ancient Maya polity of Tikal, Guatemala (figure 1). The project was unique in that it sought to investigate the relationship between settlement patterns and the regional environment, essentially studying how the ancient Maya made a living in what was perceived to be a limited tropical setting. While their work is widely recognized in lowland Maya studies, several key questions posed by the project remain unanswered. Recently, Webster and Murtha revisited a subset of the Tikal project’s original research goals, again with NSF funding (2004-2006: BCS-0443820). But here, we propose to address the core unanswered questions about the coupled natural and human history first raised by the Tikal Sustaining Area Project. Recognizing the limits of traditional archaeological approaches in addressing these questions, we propose to creatively combine diachronic climate-environmental modeling with spatial analysis of settlement pattern information. Uniquely, we are relying on a subset of niche construction theory to inform our project design. We will investigate the relationships among changing patterns of productive land, water, population and political history using climate, soil and hydrologic modeling and spatial analysis of archaeological features. The key issue we study is the changing spatial and temporal dynamics of agrarian resource availability as compared to what we know about regional political and population history.

The critical period we are studying (1000 BC to AD 2000) began with small populations and dispersed settlements, but was accompanied by widespread deforestation and soil erosion. Erosion transformed the prehistoric environment, establishing resource patches that subsequent populations relied on, i.e., pockets of eroded soil adjacent to bajo (swamp) margins. Population size and density grew rapidly for 600 years (AD 250 to 850), while deforestation and erosion rates declined. During this period, a complex cultural and political system emerged and became tightly integrated to a carefully cultivated mosaic of environmental patches. There is striking evidence of political evolution, including the construction of monumental architecture, erection of hieroglyphic monuments detailing wars and alliances, and the construction of a regional territorial boundary, possibly delineating natural resource access (Webster et al. 2007). After this period of population growth and regional political stability, the political system fragmented, followed by population decline and reforestation in patterns now influenced by centuries of previous land use and landscape change.

The recent emergence of niche construction theory in the social sciences combined with advancements in coupled computer modeling tools (i.e., linking climate, land use and environmental change) provide an ideal opportunity to investigate lowland political history and identify how natural and cultural systems intersect and interact through time. The Penn State Integrated Hydrologic Modeling System (PIHMgis) and the Erosion Productivity Impact Calculator (EPIC) are two environmental and land use simulation engines previously applied with great success by independent water and land research projects in the lowlands (French 2009; Murtha 2002 and 2009; Wingard 1996). We will employ both to model five important 100-year sample periods in the 3,000-year history of the Tikal National Park. We will compare the results of the simulations to spatial patterns of settlement features in order to interpret resource availability and its influence in regional political history. Our innovative modeling approach not only evaluates issues concerning Tikal’s cultural history, but also is designed to operationalize one of the feedback mechanisms of niche construction theory in a specific archaeological context. As Laland and O’Brien (2010) suggest, archaeological studies of niche construction provide potentially important tests of how such construction relates to evolutionary theory. Pragmatically, we will also explore these methods to identify and refine critical data and simulation needs and processes, i.e., coupling the land and water simulation engines, so that they can be potentially transferred to other anthropological contexts.

**Tikal Description:**

The research location is the Tikal National Park, a 570 km² ecological and cultural reserve located in the department of the Petén, Guatemala approximately 64 kilometers north of the Lago Petén Itza and the modern city of Flores (figure 1). The park, established in 1955 and declared a UNESCO World Heritage Site in 1979, is home to one of the most important and well-studied ancient Maya centers and polities. It is also one of the core zones of the larger Maya Biosphere Reserve, bordered on the southwest by the San Miguel la Palotada Protected Biosphere and on the east by the ancient Maya sites of Yaxhá,
Nakum and Naranjo. North of the park there is a multi-use zone of the biosphere extending to the El Mirador-Rio Azul National Park.

The landscape of the park is described as gently rolling hills. On the northwest is a range of hills that extends towards the smaller Maya center of Uaxactun. From southeast to northwest the area is crossed by uplands with a flatter topography. Average annual temperatures range between 24° C and 30° C, combined with average annual rainfall around 1,900 mm. The rainfall is seasonal, with dry months typically occurring from February to May. Over 40,000 Maya are estimated to have occupied Tikal and its immediate environs (in a > 120 km² area) during its peak occupation in the Classic Period (between AD 700 and 850) (Haviland 2003, Culbert et al. 1990). Today the Park is largely reforested, but infrastructure and the multi-use zone of the biosphere led to some development and deforestation pressures. Our study covers a 3,000-year history of the park, focused specifically on major population and political periods in Maya cultural history (figure 2).

Overview of Research Questions:

The key questions we seek to evaluate are the roles of environmental change and land use in the political evolution of the Tikal landscape. Using niche construction as a theoretical model, we specifically study how changing spatial and temporal patterns of land and water availability (for agricultural production) influenced regional settlement and political patterns. Using the earthworks as a rare emic
delineation of a cultural niche and what we know about historic settlement pattern density, we will specifically test how the built environment correlates (or doesn't) with changing patterns of agricultural resource availability through time (ecological niches). Through this research we also aim to identify what scale and data models provide effective and efficient historic coupled modeling of land use, productivity, climate and hydrologic systems in the lowlands, recognizing that simulations provide creative means to investigate long-term land use and environmental change in anthropological contexts.

**Overview of Research Tasks:**

1. Combine five decades of settlement pattern research (and data) in the Tikal region into a land use + land cover geodatabase. These data include recent surveys by project members completed in 2006¹ (Carr and Hazard 1961; Ford 1986; Puleston 1983, Webster et al 2004, 2007).

2. Examine, process, and characterize remote sensing data, (primarily multispectral images) for use in our modeling and simulations. These data will also allow us to refine the modern land use coverages (i.e., Global Land 1-KM AVHRR and 300 m GlobCover) and ultimately to develop spatial coverages of land use for the entire park².

3. Develop five 570 km² coverages (30m resolution) of land use and land cover for the national park, (essentially, spatio-temporal models of the distribution of settlements, land cover and land use). These coverages will be used in five 100-year hydrologic and soil simulations.

4. Complete five 100-year climate, land use, soil, and hydrologic simulations scenarios, using MARKSim+Bryson (climate), PIHMgis (land use and hydrology) and EPIC (land use and soil) (sample periods are defined in section 4 and illustrated in figure 4).

5. Conduct targeted field surveys of soil, settlement and water in the Tikal region, based on the results of the models. Limited fieldwork will not only allow us to test the results of the simulations, but also refine the model parameters for broader application in a follow-up project.

All the information we collect and simulate will be linked in a single spatial database allowing us to analyze the historic spatial relationships among productive land and water availability (derived from the simulations) and the evolving regional political centers, population and settlement distribution (derived from archaeological settlement patterns).

### 2.0 Background

The coupled environmental and cultural history of the lowland Maya forest potentially offers one of the world’s most compelling narratives of land use, landscape change, and niche construction. Once perceived to be a wild and pristine environment, we now know that the structure of the lowland forest has been shaped by over 3,000 years of political, economic, and population history. The study region, the forested landscape surrounding the Ancient Maya and UNESCO World Heritage site of Tikal (figure 1), Guatemala is the setting for substantial population, environmental, and cultural transformations during these three thousand years.

Between 1000 BC and AD 50 the region witnessed the transition from a mature tropical forest only lightly populated by humans to one transformed by early and dispersed agrarian settlements, who initiated widespread deforestation and soil erosion. Population size and density grew rapidly for 800 years after the early settlements, accompanied by striking evidence of political evolution, including monumental architecture, hieroglyphic monuments detailing wars and alliances, and the construction of an earthwork feature signaling a political boundary and possibly delineating natural resources (Webster et al 2007). A period of rapid population decline, commonly called the collapse (AD 800-900) followed this fluorescence and expansion. Thereafter the lowland forest gradually reestablished itself. Dispersed populations and selective logging characterized 20th century land use until more recent infrastructure development and road construction, accompanied by moderate population growth and some land use pressure in the last fifty years. During the past three thousand years the tightly integrated natural and human dimensions of soil, hydrologic, political and settlement systems have been written into the forest landscape. During the past fifty years archaeologists have developed a solid understanding of the general patterns of population and political history in the Maya lowlands. Recently, we’ve also come to better understand the interaction between land use (deforestation) and climate (Oglesby et al 2010). But how these played out in a specific

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¹ All of these data are now in digital form and will be combined into a single geospatial database as part of this effort (see figure 3).

² We have acquired high resolution IKONOS data, AIRSAR, and LandSAT ETM+ coverage.
regional context such as Tikal’s is poorly understood. Moreover, how cultural and ecological patterns intersected regionally throughout Maya political history (regionally) at many sites remains understudied. Several of our project members recognized this issue after completing research at Tikal recently.

In 2003, Webster and Murtha participated in an NSF project to better document the remains of a famous but enigmatic boundary marker found on the peripheries of Tikal, building on research originally conducted by the Tikal Sustaining Area Project in the 1960’s. The project specifically investigated the earthwork and its immediate context in order to understand its relationship to the political history of Tikal. Unlike other earthworks or similar features in the lowlands, the boundary was constructed between 5 and 10 kms distant from the center of the city of Tikal, reflecting what has long been considered a unique emic perception of an agrarian landscape. First identified in 1966 (and excavated as part of an NSF project in 1967), the feature became central to calculations of Maya settlement and population distribution and interpreted as a means to define the agricultural sustaining area of the city. We found the feature to be incomplete and larger, more expansive, and more complex than previous research had suggested (see figure 3) (Webster et al 2007). Contrary to predictions of the sustaining area model, we did not observe significant differences in population densities inside and outside the earthwork nor did we observe any differences in past productive patterns (Burnett et al 2011). And while the northern boundary followed a relatively linear east-west alignment, the east and southern remains were not aligned linearly. In fact, eastern earthwork remains were more associated with natural landforms and regionally important centers, including Ramonal-Chalpate (figure 3).

Figure 3. Map of the Tikal National Park illustrating watershed boundaries (grey dashed), the earthwork (red), areas surveyed in the past 60 years (blue), and large regional sites (black square) with significant landscape features labeled.
In light of our research, several questions about the spatio-temporal organization of Tikal’s regional settlement, land, and water resources arose. For example, while we can now better understand and interpret the chronological significance of the earthwork as it relates to certain elements of Tikal’s political and population history, we have yet to sufficiently study how it relates to the past agrarian landscape and changing dimensions of natural resource availability. We quickly generated some propositions and general questions about Tikal’s agrarian system and landscape, including:

At Tikal the principal forms of agrarian capital – soil and water – initially had regionally rather even spatial distributions. As a result of human-induced changes or niche construction, by at least AD 250 high quality land and water conditions were likely concentrated in distinct patches within watersheds. Patches were both differentially productive and differentially risky, probably causing variation in household well-being and incipient economic stratification. Distribution and extent of such patches, along with the political circumscription of nearby polities, stimulated the perception of an agrarian hinterland that came to be defined by formal political boundaries (Webster et al 2004). But how does the changing mosaic of resource patches correlate to the construction of the earthwork?

Early agrarian settlements and deforestation associated with land use initiated substantial erosion in the Tikal watershed. Eroded soils accumulated in bajos and around their edges, creating new, distinctive ecological niches. Classic populations exploited these new niches (Anselmetti et al 2007; Dunning et al 2002; Beach et al 2006). Infilling of bajos by soil altered movement of water through the watersheds, thereby changing its availability for household use and potentially influencing regional population distribution and the political influence of Tikal’s elites (Dunning et al 1998, 2002; Beach et al 2006). But how were these patches distributed through time and how did they influence regional population density?

During Preclassic times, when productive land and water were widely distributed and population densities were low, the effects of severe climactic events, e.g., droughts were broadly similar across the landscape. Local populations adapted to them through spatial relocation and adjustment of agricultural strategies. By Classic times droughts differentially affected different resource patches within local watersheds, although probably not the watershed as a whole. Major droughts such as those postulated for the Terminal Classic (AD 770-870) posed even larger problems for land and water use. Overall, during the Classic period cultural niches (or land use traditions) likely played as important a role as ecological niches. Such conditions stimulated not only deteriorating productivity but also internal competition and stress. Were some parts of the Tikal landscape more or less resilient? Is that resilience reflected in the settlement patterns (e.g., length of occupation or density)? How did deforestation and climate interact regionally (e.g., surface albedo or evapotranspiration see: Oglesby et al 2010)?

After consideration, we realized that these questions were central to the original Tikal project carried out four decades ago. But we believe that recent developments in niche construction theory combined with computer modeling provide a new means to operationalize and investigate them.

Niche construction is, “the process whereby organisms, through their metabolism, their activities and their choices, modify their own and/or each other's niches (Odling-Smee et al. 2003: 419).” Olding-Smee and others have demonstrated that niche construction plays a key role in regulating hydrological, nutrient, and element (e.g., carbon) cycling (Odling-Smee et al. 2003). Because humans are demonstrative niche constructors (Smith 2007:188) understanding how niche construction relates to cultural history is central to understanding the impact of past human populations on their environments (Laland and O’Brien 2010). According to Olding-Smee and colleagues, niche construction can be inceptive or counteractive, i.e., initiate change or respond to change and result in perturbation or relocation, i.e., organisms physically modify their surroundings or move to a more suitable location. By isolating productive elements of soil and water availability, we believe we can study Tikal’s cultural and environmental history through changing patterns of inceptive or counteractive change resulting in perturbation or relocation. Using this model, the collapse of the Maya, for example, could be conceived of as a final act of counteractive relocation. Later in the proposal we identify how each period of our simulation may reflect changing patterns of niche construction.

There is an additional element to the application of niche construction theory to anthropological cases that we rely on. As Hardesty (1972) commented, culture is the human ecological niche. So while humans engage in inceptive and counteractive perturbation and relocation, they also evolve transgenerational
cultural niches or ‘traditions’. This principle provides us with the interpretive framework specifically to better understand the earthwork boundary in both cultural and ecological contexts. For decades the archaeological expectation was that the earthworks signified a defined cultural boundary between quality productive land and poor productive lands or at least a hard boundary between intensive and extensive land use practices. Traditional archaeological expectations also suggested that there would be smaller populations outside of the earthwork boundaries. Both of these expectations were refuted by our recent research. Niche construction now allows us to evaluate the earthwork boundary not as a static representation of past perceptions of agrarian landscape, but an actively negotiated boundary, or a ‘cultural niche’ (Olding-Smee et al 2003).

Unlike past evolutionary approaches in archaeology, niche construction theory allows social scientists to look beyond environment as a one way cause of culture change and evolution, (e.g., common models of the Maya collapse that rely on a single external factor such as a drought) and investigate the mosaic of environmental and cultural niches influential in different periods in Tikal’s political history. Perhaps our perspective is oversimplified for presentation purposes in this proposal, but by using this approach we aim to evaluate niche construction as a primary process in the evolution of organizational complexity in the lowlands. We will model the spatial pattern of both ecological and cultural niches in the Tikal region, recognizing that coupled cultural and ecological systems were influential in the emergence of political complexity, sustained management of the system and the collapse of the Maya.

3.0 Research Questions:

We developed the following specific research questions to be addressed in this exploratory project:

1. What were the environmental and landscape effects of ancient Maya settlement, growth, expansion, and eventual depopulation? Specifically, what were the quantitative effects of deforestation and increasingly intensive agriculture on water and soil availability throughout the watershed? While broad chronological patterns of deforestation are known regionally, we will specifically quantify spatial patterns of environmental change during the sample periods, e.g. erosion.

2. How did the Maya respond to these transformed resources and so maintain and manage them through time and across the landscape? In other regions of the lowlands there is clear evidence of intensification of agriculture and maintenance of natural resources, e.g., terracing on the Vaca Plateau, Belize (Murtha 2009), but there is virtually no similar evidence in the Tikal watershed (Webster et al 2004).

3. How did the changing availability of resources influence the built environment or spatial arrangement of settlement, including emic statements of territory and polity size, such as the earthworks and regional political centers? And did seasonal extreme variations in precipitation, i.e., droughts, differentially influence these patterns?

4. What is the role of niche construction during these key periods in Tikal’s political history (see figure 2 for overall Maya chronology):
   - The Preclassic period (1000 BC to AD 100) is marked by early agrarian settlements and the construction of early monumental architecture, such as the Mundo Perdido (Laporte 2003).
   - The Late Preclassic to Early Classic transition (AD 100 to 378) is characterized by population growth and the establishment of Tikal’s early dynasty. Especially important during this period is the emergence of historical texts.
   - The Early to Middle Classic period (AD 378 to 562) is characterized by population growth and the centralization of power. Warfare increases as regional polities mature (Martin 2003).
   - The mini-hiatus period during the Early Late Classic (AD 562 to 692) is marked by a decrease in monumental construction and hieroglyphic references, but no significant change in regional population size and distribution (Haviland 2003). During the Late Classic (AD 692 to 869), Tikal’s central authority flourishes and significant monumental constructions are completed. Dense populations are dispersed in patches throughout the region.
   - After AD 869 there is evidence of sustained population decline and a collapse of political activity.

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3 Dunning (2011) indicates that he identified small features that may be terraces adjacent to bajo margins.
While researchers have probed these questions independently or indirectly for fifty years, several developments now allow us to combine and address these questions in new and innovative ways:

- The breadth of previous research completed at Tikal and our capacity to create a digital archive of settlement data allow us to compile one of the largest detailed settlement databases for an ancient tropical environment. Our recent project emphasizing the earthwork and regional settlement provides a more sophisticated understanding regional political negotiation and an emic window into perceptions of the Maya landscape and regional boundaries. Defining site or hinterland boundaries has been a consistent problem for archaeologists working in the central lowlands and the new information derived from our earthwork research illustrates how the Maya elite attempted to define and delineate territory (Webster et al 2004).

- Advances in remote sensing, especially the availability of environmental data, now allow us to better characterize the natural and cultural features of the lowland Maya landscape. We already have detailed models of Tikal’s topography, soil, and modern land use/land cover prepared for analysis.

- Recent advances in environmental modeling, specifically, Duffy’s recent development of PIHMgis and the increased use of formal watershed/climate simulation in archaeology and anthropology, have opened the opportunity to apply coupled climate and environmental models to issues addressing long-term human land use and environmental change. We advocate that this project as an innovative way to address deep time issues concerning population, land use and natural resources availability in the lowland tropical forest, relying on published and recent research, existing environmental data and new developments in spatially integrated environmental simulations.

- We now recognize that these key questions cannot necessarily be answered by traditional archaeological methods. There’s no new mapping method or prospection technique that will provide as useful an interpretive framework as computer modeling can provide. We realize that the modeling will not provide a high-resolution (spatially and temporally) image of the past, but it allows us to isolate key influential variables and test their influence through time. Independently, several of us have used modeling with great success, so we are familiar with the benefits and limitations of such an approach (French 2009; Murtha 2009).

4.0 Research Design:

We have designed an integrated environmental and archaeological approach, relying on computer modeling based on geospatial databases, climate reconstruction, limited field survey and spatial and temporal analysis. Our primary objective is to evaluate the utility of applying interdisciplinary data and models for interpreting the distribution of known cultural features (human dimensions) in relation to physical features (natural dimensions). For purposes of an efficient simulation and modeling process, we have selected five 100-year samples reflecting key periods of regional land, water, population and political history (figure 4). We have also indicated how each period can be framed via niche construction theory.

1) 1000 BC to 900 BC – primary forest to long fallow early agrarian settlements (inceptive perturbation);
2) 200 BC to 100 BC – increased intensive land use accompanied by deforestation and erosion, but moderate population growth and pressure (counteractive perturbation and relocation);
3) AD 450 to 550 – Classic Period settlement and population growth accompanied by substantial political activity and probable land availability pressure (counteractive perturbation);
4) AD 750 to 850 – end of the Classic period, accompanied by decreased productivity and the beginning of population decline (counteractive relocation and perturbation); and,
5) AD 1900 to 2000 – the modern era, including the establishment of the Mayan Biosphere Reserve and the construction and settlement of the Tikal Road (inceptive perturbation).

For each of the periods, we will first generate historic and paleoclimate daily weather using MarkSIM and the Bryson Archaeoclimatology Macrophysical Climate Model (BMCM). Second, we will generate five 100-year land use, soil, and erosion simulations (e.g., scenarios) using EPIC and PIHMgis (see figure 4 and table 1). Validation will be performed on existing and project data from the modern record. Third, we
will compare the simulations to the compiled information about Tikal’s historic and prehistoric settlement patterns. Finally, we will conduct targeted field studies (soil, water and settlement) to test the efficacy of the simulation results in year two and analyze the evolution and spatial patterns of land use and natural resources at Tikal through time.

Figure 4. Diagram illustrating the relationships among soil erosion, forest cover, maize production and population history. Our sample periods are highlighted. The diagram relies on historic environmental data reported in Anselmetti et al. 2007 and Rosenmeier et al. 2002a, 2002b and settlement data reported in Haviland 2003).

4.1 The Tikal Paleoclimate Model (Step One) – French, Duffy and Murtha

Our interest here is in developing a statistically plausible paleoclimatic history for Tikal using a weather and climate generating programs that capture long-range climate variations (1000 BC to AD 2000) and short-range weather statistics. To generate this information for the five 100-year periods, we will use the following programs:

**MarkSim** is a weather generator traditionally used for crop modeling and risk assessment based on the instrumental record from 9200 tropical weather stations for Latin America and Africa. The stochastic weather generator uses a third-order Markov process to model daily precipitation, temperature, etc. The daily data provided by the model preserves the statistics of regional data. The climate normals for these stations were assembled into 664 groups using a clustering algorithm. For each of these groups, rainfall model parameters are predicted from monthly means of rainfall, air temperature, diurnal temperature range, station elevation, and latitude. The program identifies the cluster relevant to any required point using interpolated climate surfaces at a resolution of 10 min or arc (18km2) and evaluates the model parameters for that point (Jones and Thorton 2000). For Tikal, we will use the MarkSim generator to construct a data set of rainfall and temperature over the last 100 years, similar to work previously conducted at Palenque, Mexico (French 2009: 178-183).

**Bryson Paleoclimate Model**

For purposes of this project, we are using the Bryson model as a test bed to isolate the potential influence of climate. Bryson is a community model that we will test as a strategy to generate synthetic climate realizations but we will research the use of other models that may provide “reconstructions” rather than simply a statistical realization of climate.
The second component of our climate model uses the Bryson Archaeoclimatology Macrophysical Climate Model (BMCM), a high resolution, site specific, macrophysical climate model. The BMCM was developed in the mid-1990s by Reid A. and Robert U. Bryson as an alternative to general circulation models (GCMs) that could produce results at a spatial and temporal scale useful to a variety of social, natural and earth sciences. Unlike the wide assortment of GCMs in the literature, the BMCM takes a top-down, rather than bottom-up, approach to model building. The output of the model now allows for 100-year averages in calendar years (R. U. Bryson et al. 2006). The foundation of the BMCM is the calculated “modules” that provide the location of each of the centers of action for the past 40,000 years, in 100-year intervals of monthly values. Each module contains the locations (latitudes) for one center of action at a given longitude. Twenty different modules in four categories are utilized by the BMCM, but only four to six are present in any given model. The breakdown is as follows: temperature modules, highs, Intertropical Convergence locations (ITC), and jet stream locations. The BMCM is, in essence, a heat-budget model predicated on orbital forcing, variations in atmospheric transparency, and the principles of synoptic climatology (Bryson and DeWall 2007). Average monthly rainfall, maximum and minimum temperature, and mean temperature typical of Tikal will be entered into the BMCM and a dataset of 100-year averages for the last 3,000 years will be generated (similar to French 2009: 187-189).

MarkSIM + Bryson

It is important to restate that the purpose of this analysis is to construct plausible hydrologic inputs into the land use models (EPIC and PIHMgis), while preserving the short-term daily to seasonal statistics of precipitation and temperature while also maintaining the long-term climate variations and patterns in the paleoclimate model. Using the method of proportionality (IPCC 1996), the daily 100-year MarkSim simulations will be scaled by the climate trends of the Bryson model to produce 100-year daily scenarios for each of the five selected centuries of our study. This approach therefore provides an inference and index of past conditions and watershed inputs. It will also allow us to study input thresholds in a regional setting.

4.2 Land Use, Soil, and Water Model (Step Two)

Perhaps the key concern of our proposed research is in developing plausible spatial representations of land use, landscape change and resource availability for Tikal using environmental modeling and simulation programs that capture long-term environmental change and response to annual climate variation, including extreme annual precipitation shortages. The purpose of these programs is to generate temporally linked spatial models of resource availability relying on changing patterns of land use, i.e. generally speaking from extensive management to intensive and sustained agricultural production. In both simulation engines we will input daily weather data generated in step one. We will use the following programs:

1. **EPIC (Erosion Productivity Impact Calculator)**, relying on climate data generated by MarkSim and BMCM will be used to simulate the effects different land use and management strategies on soil erosion and agricultural production. Particular emphasis will be placed on evaluating the spatial effects of extreme climate events such as droughts on productivity but the key purpose of these simulations is to model the effects of sustained agricultural production throughout the Tikal watershed (similar to Wingard 1996 in the Copan Valley and Murtha 2009 on the Vaca Plateau); and,

2. **PIHMgis** will be used to simulate the effects of land use, land cover, and changing patterns of soil erosion on water movement and availability. Particular emphasis, again, will be placed on evaluating the effects of extreme climate events on water availability/distribution, but the key purpose is to analyze the effects of land use change, primarily deforestation, erosion and sustained agricultural production throughout the watershed on regional water, distribution (including soil moisture).

We will not use the modeling to reconstruct a past replica of Maya settlement, land use and natural resources, but as an inferential window to measure how what we know historically about environmental, political and population patterns, played out spatially. We use these models and simulations to quantify the overall effects of climate variation, long-term decision-making and natural resource availability in the watershed given a climate and land cover regime (during each 100 year sample period).
4.2.1 EPIC and Simulating Land Use, Soil Erosion and Productivity – Murtha and Webster

Several computer programs are specifically designed to simulate biomass growth, erosion and crop productivity. Perhaps the most robust engine, EPIC, was initially designed to provide agronomists with the ability to evaluate long-term productivity considerations in relation to local soil and climate variables in the US. While it was developed for use with prepared data sets of modern US States and counties, it has been employed to simulate crop production in a variety of natural settings by Penn State archaeologists. For example, the EPIC program was successfully used at Copan, Honduras, by John Wingard (Wingard 1992, 1996), to evaluate the role of population and soils in the development and collapse of Copan and by Murtha (2002, 2009) to understand the relationships among soils, population and agricultural terracing over a 1000-year period at Caracol, Belize. In the latter case, simulation results from EPIC were integrated within GIS (Murtha 2009).

Land management data entered into the land use model of EPIC will be a simplified version of Murtha’s (2009) approach in Belize to reflect commonly understood management techniques (and the intensity of land use) and crops used in the Maya area (Table 1). Each of the 100-year simulations will be run for a combination of the three land management strategies. The intensity of land use will be selected as compared to documented population and environmental history at Tikal (Haviland 2003) (see Figure 4). The simulation data will be queried for key erosion and productivity measures and integrated to the overall Tikal GIS model. Productive land will be classified and studied for each simulation period using standard spatial configuration landscape metrics. Importantly, we are interested in identifying the degree to which different classes of productive land are clustered or dispersed throughout the study period. When used in a similar context, Murtha (2009) demonstrates that the construction of terraces at Caracol, Belize resulted in dispersed agrarian system with similar resource access regionally. Because of the lack of terracing and the general physiography of Tikal we anticipate a clustered distribution of quality productive land as population grows in the region.

Table 1. Land Management strategies we will use in EPIC.

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<tr>
<th>Strategy</th>
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<tr>
<td><strong>Fallow (Traditional Milpa)</strong>: The fallow management strategy consists of eight years of fallow, followed by two consecutive years of maize production. Fields are first burned in year 8 and the first maize crop is planted on May 1st or on the first optimal day after May 1st (the optimal day relies on ground temperature measured as potential heat units derived from the climate data). Two weeding operations will be coded into the management strategy, first on May 30th and then on June 30th. The maize crop is harvested on August 15th, and followed by a bean crop.</td>
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<tr>
<td><strong>Short Fallow (SF)</strong>: The short fallow management strategy consists of three years of fallow, followed by two consecutive years of maize production. The operations and timing of the operations followed the same schedule as the Medium Fallow management system, including the bean crop.</td>
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<tr>
<td><strong>Annual Cropping (AC)</strong>: The annual cropping scheme eliminated all fallow years coded for the three previous management strategies and followed the same schedule as the Medium Fallow management system, including the bean crop.</td>
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4.2.2 Integrated Modeling of Watershed Dynamics – Duffy, French and Webster

Major hydrological processes within the terrestrial hydrological cycle operate over a wide range of time scales. Interactions among them range from uncoupled to strongly coupled. Numerical simulation of coupled nonlinear hydrologic processes requires an efficient and flexible approach. PIHM (Penn State Integrated Model) represents a new strategy for watershed modeling where the subsurface and land surface processes for water and energy are fully coupled and spatially distributed. Our approach reduces governing partial differential equations (PDE) to ordinary differential equations (ODE) using the semidiscrete finite volume method (FVM) (see http://www.pihm.psu.edu/). The finite volume elements are prisms, projected from the TIN generated with constraints. The model is designed to capture “dynamics” in multiple processes while maintaining the conservation of mass at all cells, as guaranteed by the finite volume formulation.

The “control-volume” in the finite volume formulation is a prismatic or linear physical element, which is also called model kernel with all the physical process equations and constitutive relationships identified. PIHM and PIHM_GIS represent a community modeling tool and GIS tool developed under NSF Hydrologic Sciences funding for scientific application to Hydrologic Observatories. This effort serves as a test of our overall modeling strategy to demonstrate the utility of integrated models for un-gauged (or
nearly un-gauged) basins, including the atmospheric forcing to the watershed for water resource assessment. The important distinction of PIHM from other watershed models is that the physical layers and data-layers for each projected prismatic element are explicitly linked (tightly coupled) through a data-model and GIS interface.

PIHMgis is an integrated and extensible GIS system with data management, data analysis, data modeling, unstructured mesh generation and distributed PIHM modeling capabilities. The underlying philosophy of this integrated system is a shared geo-data model between GIS and the watershed model (PIHM) thus making it possible to efficiently handle the complexity of the different data models, representation structures and model simulations, and to rapidly produce new prototype scenarios for climate and land use. PIHMgis has the capability to perform complex data modeling (soil parameters, geology, etc.), parameterization, hydrologic modeling, data/model analysis and visualization with a tight coupling of data handling, parameterization and simulation. The open architecture is particularly suited to the rapid prototyping of new model functions in support of diverse hydrologic modeling applications.

4.2.3 Evaluation of the simulations

PIHMgis and EPIC will simulate all of the environmental variables for water, energy and sediment dynamics. The critical variables to be used to compare resource distribution through time and define areas for the field survey (see step four) are described next.

1. Erosion (EPIC + PIHMgis): While erosion is chronologically documented throughout our study area and period (Figure 4), we are particularly interested in identifying patches of heavy erosion during simulation periods 1, 2, and 3 and comparing those areas with erosion during the Classic period, or simulations 4 and 5. These simulations will not only identify marginal areas for agricultural production and how those areas shift through time, but also document what agricultural niches were transformed (or ‘engineered), by earlier activities. The integrated hydrologic model PIHM for water and energy will be 1-way coupled to EPIC such that terrain elevation and land cover will be updated on a weekly or monthly basis in PIHM which will have hourly time step to capture large storm events. If we can, we will fully couple EPIC and PIHM, which will allow the most complete simulation of water-energy-land cover, and sediment transport.

2. Productivity (EPIC): Similar to Murtha (2009), we will compute productivity trends for the entire agrarian landscape, allowing us to identify specific patches and regions that exhibit evidence for sustained agricultural production under different management strategies. Such an approach will allow us to differentially classify the agrarian landscape during each sample period and compare this information to documented historic population densities (estimated from settlement data). It will also allow us to disentangle the influences of erosion and nutrient loss for sustained production on the Tikal soils.

3. Groundwater-Soil Water (PIHMgis): The Tikal region was and continues to be dependent on hydrogeologic conditions and seasonal precipitation. The hydrogeologic conditions at Tikal are much different previous applications at Palenque (French 2009), with both shallow (perched water table) and deep groundwater table conditions encountered at the site. The sedimentary basin at Tikal has deposits from the Mesozoic and the Tertiary periods, which contain limestone and dolomites with karst formations and middle relief. Soils are clayey and slightly permeable, with internal drainage, and easily compactible. Through century-long EPIC-PIHM simulations we will identify the distribution of poorly-drained and well-drained agricultural patches for assessing agricultural production. And patches where flooding and erosion are likely to degrade crop production. This analysis will also allow us to compare how regional and large scale changes in precipitation-runoff and erosion could have affected households. We will also evaluate how deforestation and climate interact as measured by surface albedo and evapotranspiration (see Oglesby et al 2010).

The above EPIC-PIHM simulations will assist in identifying targeted field surveys for year two and provide a foundation for evaluating the watershed response for five 100-year scenarios of climate and land use change. Detailed flood, drought, erosion frequency analysis will be carried out for each 100-year regime and the landform-landcover response variables will be evaluated. Since the simulation results are spatially linked to the landscape, we will be able to query and divide the landscape into critical natural resource patches, relevant to agricultural productivity and water availability. We will then compare these queries to the database of surveyed settlement features (step three).
4.3 Comparison of Soil, Water, and Settlement Model (Step Three) - All

The Tikal region has been the focus of a number of settlement pattern studies in the past six decades. We will compare these data to the environmental models derived from the five 100-year simulations in order to evaluate the spatial distribution of known settlement to the changing patterns of land and water availability during our periods of study. For example, the five 100-year simulations will be compared to the earthwork boundary, large regional centers and the distribution of surveyed house remains in the Tikal hinterland. We will rely on standard landscape metrics, i.e., relating settlement densities to the patches and boundaries defined in step two (Murtha 2002, 2009). The key component of this step is to test the spatial correlation (or lack thereof) between ecological niches (as modeled through soil and water simulations) and cultural niches (as measured by archaeological remains, including the enigmatic earthwork). A similar set of comparative analyses of landscape data and archaeological remains has been conducted in other settings successfully (Murtha 2009).

4.4 Environmental and Settlement Survey (Step Four) – Murtha, French, Terry, and Webster

At the end of the dry season in 2013 we will complete limited landscape surveys, informed by first year results. We will sample .5 to 1km transects in each the following regional settings where we expect critical land, population and water issues to intersect (figure 3):

1. The Santa Fe Bajo (Distant Bajo Margins) – located east and northeast of Tikal the Santa Fe Bajo is perhaps the most significant feature of Tikal’s landscape. It is the largest drainage for the region and long has been considered a potential breadbasket for wetland agricultural production.

2. The Southeast Upland Ridge – Following the Arroyo Negro south, there exists an impressive upland ridge to the southeast of Tikal where evidence for the earthwork disappears. This region shows clear, albeit not dense, evidence of settlement. Located east of the Arroyo Negro, this region is one of the most concentrated areas of well-drained upland soils in the Tikal region.

3. The Western Bajo and Southwest Ridge – Largely ignored by research prior to 2003, our settlement pattern study and earthwork study show a clear pattern of spatial distribution of settlement adjacent to the western bajo and uniquely coupled with the earthwork. The bajo is structurally different from the Santa Fe bajo, i.e., it is a logwood bajo.

4. The Northwest Upland Ridge -the significant Upland Ridge located between Tikal and Uaxactun (bordered on the south side by the earthworks). The undulating topography of this region and its position adjacent to the earthwork allows us to evaluate landscape, environment and settlement issues on a smaller scale, more effectively sampling Maya houses, small agricultural fields, water features, and bajos.

Using transects defined in these regions, we will sample and study soil profiles for evidence of erosion, past agricultural production, prehistoric settlement and surface water availability. Our soil samples will be evaluated for basic chemistry, including moisture content and compared to the erosion and hydrologic models developed in EPIC and PIHMgis. One week of fieldwork will be devoted to each sample area. We will perform the settlement survey, relying on dGPS, which will also provide the baseline transects for the collection of soil samples. Augured soil samples will be collected along each transect, spaced every 100 meters. Twelve profiles will be collected for each sample area and returned to the US for basic chemistry and stable isotope analysis. A systematic water survey will accompany the settlement survey, where we will identify and field check: 1) evidence for past water storage (small aguadas) and 2) natural water features predicted by our PIHMgis simulations. Upon completion of our fieldwork, we will complete the laboratory analysis of soil.

Settlement and Water Survey Methods: Settlement survey methods will follow standard lowland survey techniques (see Webster et al 2004). The four transects will be cut along north/south and east/west bearings. They will be staked every 100 meters and reconnaissance teams will walk at evenly spaced intervals marking and mapping all identified features. Each observable feature, once encountered is cleared, tagged, and prepared for mapping. Settlement features and water features will be surveyed using dGPS, specifically using Magellan (Thales) Mobile Mapper units with a mobile base station for post mission correction.

Soil sampling and analysis: Concurrent with the settlement and water survey we will also acquire 60 soil profiles for analysis. Samples will be retrieved at 100-meter intervals along a north/south and east/west transect. Soil profiles will be augured and returned to Terry’s lab at BYU for laboratory analyses of texture, structure, pH, organic C, carbonate C, total N, major elements, and extractable nutrients (P, K, Ca, and Mg). Soil profiles will also be analyzed to establish a vegetative history of C3 and C4 plants.
Prior research in the Maya Lowlands has used stable carbon isotopes contained in soil humus as a promising venue for delineating ancient fields used for maize agriculture (Johnson et al. 2007; Fernandez et al., 2005; Webb et al. 2007; Wright et al., 2009) because ancient soils reveal elevated or depleted levels of δ13C as a result of maize cultivation (Boutton et al. 1996; Webb et al. 2004, 2007. Once the profiles are physically and chemically analyzed, soil resource maps will be generated and areas of ancient maize cultivation will be determined by examination of carbon isotope ratios of the soil organic matter.

In our field survey, we will also look for karst sinks that have received deposition to study potential erosion histories by using the above methods. From our previous work, Burnett et al. (2011) recently reported on the δ13C isotope evidence of ancient maize agriculture in soils from upland and lowland locations near Tikal, Guatemala. The toe-slopes and lowland bajo locations contained soils with strong isotopic evidence of C4 vegetation likely the result of ancient maize agriculture, while the evidence from the upland soils was less conclusive because of the significant erosion documented.

5.0 Research Schedule:

**Year 1 (July 1, 2012 to April 30, 2013):**

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<td>(1) Compile the full array of archaeological surveys from Tikal in a single geodatabase.</td>
<td>(1) Generate five 100-year daily climate data sets using MarkSIM and BMCM.</td>
<td>(1) EPIC and PIHMgis simulations for each of the five 100-year periods.</td>
<td>(1) Compare simulation results to known archaeological features and define four transects for field survey.</td>
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<tr>
<td>(2) Compile spatial coverages for the five simulation periods of our study.</td>
<td>(2) Arrange for work permits at the Tikal National Park.</td>
<td>(2) Finalize work permits and travel arrangements for fieldwork.</td>
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**Year 2 (May 1, 2013 to June 30, 2014):**

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<td>(1) Complete five weeks of limited field survey in the Tikal region.</td>
<td>(1) Present preliminary findings at the IDAEH national meetings in Guatemala City.</td>
<td>(1) Finalize analysis and prepare final report and monograph.</td>
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<td>(2) Refine EPIC and PIHMgis simulations.</td>
<td>(2) Prepare and submit manuscripts of the results of the project.</td>
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6.0 Expected Project Significance and Conclusions:

Recent research at Tikal, combined with advancements in niche construction theory and geospatial modeling, provides a unique opportunity to document, analyze, and interpret the three thousand year history of settlement and political ecology of the Tikal National Park. Our proposed project builds upon previous research and integrates these new advancements in a creative and exploratory manner. We are proposing to explore this combined environmental modeling approach at Tikal in order to answer long-standing questions and design a future project that will explore these issues throughout the Maya lowlands. Our proposed project is significant for several reasons:

1. We will better understand the evolving settlement ecology of Tikal, thereby interpreting the formation of over three thousand years of political, economic, environmental and demographic history in the central lowlands. This includes:
   - A more complete understanding of the relationship of historic intra-site settlement networks, patterns of agglomeration and dispersion. We will also be able to model how these patterns changed through time and how they relate to agrarian resource availability.
   - To build upon the findings of the Tikal Sustaining Area Project and identifying the ecological factors influencing household placement/construction through space and time.
   - To further develop the recent findings by Webster and colleagues (2007), concerning the construction and meaning of the earthworks at Tikal.

2. We will address the significant and yet unanswered question about agricultural intensification at Tikal. Clearly, agricultural intensification occurred at all sites throughout the Maya lowlands (Murtha 2002). And yet despite our acknowledgement of this, little or no demonstrative
physical evidence has been recovered at Tikal. Longitudinal simulation has proven useful for understanding these issues in other settings (Murtha 2009).

3. We explore the spatial dimensions of land and water history in the Tikal region more effectively linking changes in land use with availability of quality soil and water through time on a landscape scale. For example, Tikal has long been the poster-child for claims that the Maya had sophisticated water-control systems and that manipulation of them by elites was one lever to power and political centralization. Most well-developed for Tikal, such arguments have been applied much more widely to the Maya. They have never been convincing to us and in fact have never been tested by any sophisticated hydrological model for the region. Our project will provide just such a test.

4. We will be able to evaluate how annual climate shifts influenced regional settlement patterns or perhaps more importantly how seasonal shifts affected households’ ability to respond to shortages or significant erosion events spatially and to generally investigate the role of niche construction in the cultural history of the Maya.

More generally, this exploratory research will allow us:

1. To investigate how formal environmental modeling can be better integrated in the lowland tropics across a variety of spatial scales to study long-term environmental change.
2. To identify effective and appropriate uses of formal environmental simulations for application in field survey, specifically anthropology and archaeology.
3. To integrate the results of PIHMgis and EPIC, thereby linking agricultural land use simulations within a coupled hydrologic model.

Our proposed two-year project examines the relationships between environmental transformations and cultural history at Tikal, Guatemala for a three thousand year period. Essentially, this project investigates a particular case study of niche construction and the issues we are evaluating are examples of what Olding-Smee, Laland, and Feldman (2003: 46–47) characterize as the categories of niche construction. Extending their use of their binary categories to our particular setting, inceptive or counteractive and perturbation or relocation, Tikal’s settlement and political history can be reasonably described as a series of evolving niche construction processes. Traditional archaeological approaches to studying these issues over the past four decades has not resulted in general consensus about the coupled environmental and cultural history in the lowlands. We propose this project, combining climate-environmental modeling, spatial analysis of settlement patterns and limited field surveys to address these questions as a new approach to unravel the complex narrative that is the ancient Maya landscape.

7.0 Dissemination and Impact

Generally speaking, as an exploratory project, we believe the most direct impacts of this research are within and across our disciplines through key publications and presentations. The uniqueness of the project members’ backgrounds provides a variety of presentation and publication venues. We will submit manuscripts for the individual elements of our project to journals we have evidenced experience with, including (but not limited to): Landscape Research, Latin American Antiquity, Journal of Archaeological Science, Landscape Journal, Soil Science Society of America Journal and Science. As several members have previously, we will also prepare a monograph reporting the results of this research (targeted for: June 2014). We are already planning to report the results of this research in international meetings, beginning in 2013:

- Council of Educators in Landscape Architecture Meetings – 2014
- American Anthropological Association Meetings - 2014

But we also designed the project to take advantage of the diverse educational and research environments of our senior personnel. We represent four departments in four colleges. The engineering post-doc will work directly with the graduate student from anthropology and undergraduate students from landscape architecture and soil science. We’ve specifically designed these vertical and horizontal collaborative opportunities to tap into the strengths of the departments represented in the project, i.e., the five year
professional undergraduate program in landscape architecture, the strong PhD program in anthropology and the post-doc tradition in engineering. We anticipate that this unique collaborative opportunity will influence each in their professional and academic careers.

7.1 Results of Previous NSF Research

While we have not received CNH funding for our work in the past, each of us has participated in NSF supported research (award IDs indicated) that directly influenced this proposal:

Timothy Murtha studies settlement patterns and the long-term sustainability of human settlements. He recently focused his research on the recent settlement, landscape, and demographic history of Orkney, Scotland (NSF: BCS 0527539, REU 0353527; Murtha et al 2009, 2010). Relying on historic maps, remote sensing and field survey he constructed a diachronic model of demographic change and land use (Murtha et al 2010). That work has been the basis for over 25 international presentations and publications in the past five years. The project supported two PhD students, three MA students, and 30 undergraduate research assistants between 2004 and 2010. In addition to that work, Murtha has spent considerable time working in lowland Central America, including research addressing the political and settlement ecology of Tikal (NSF BCS 0443820; Murtha 2010; Webster et al 2008, 2007, and 2004). Three MA students and one PhD students were supported by this research.

From 1988 to 1994, Christopher Duffy was principal investigator for a series of USGS projects (14080001G1630) and NSF research (EAR-9017724; 1991-1994) regarding the hydrology and hydrogeology of the closed basins in western Utah and eastern Nevada. This research led to several publications focused on time series analysis of historical hydroclimatic records and numerical modeling experiments of fresh and saline water in closed basins (Duffy and Al-Hassan 1988; Duffy 1990; Fan and Duffy 1993; Fan, Duffy and Oliver 1997; Shun and Duffy, 1998). The 2-D numerical experiments of Duffy and Al-Hassan (1988) simulated haline convection in closed basins. Later, Duffy's work focused on physically-based low-dimensional modeling strategy in complex terrain, funded by the ARO (DAAH04-96-1-0035,1991-1994), NSF (EAR 9418674, 1995-1998) and NASA (.NAGW 4401, 1995-1998). For the last 4 years Duffy and his team have focused on developing the fully distributed, physics-based modeling code PIHM (Penn State Integrated Hydrologic Modeling System) for multi-scale, multi-process applications. This research is funded by NSF: Integrated Modeling of Precipitation¬ Recharge-Runoff at the River Basin Scale: The Susquehanna” (EAR-0310122, 2003-2006). The theory is developed in Qu and Duffy (2007). Three PhD dissertations from this research have been completed: Y. Qu (2004), M. Kumar (2009), and S. Li (2008). Presently Duffy is the lead PI on the 5-year NSF-funded Shale Hills-Susquehanna River Basin Critical Zone Observatory (2007-2012).

David Webster focuses on Mesoamerican, especially Lowland Maya, archaeology. He has had many field projects in Mexico, Guatemala, and Honduras. Professor. Webster's most recent field project was Re-evaluation of the Earthworks at Tikal, Guatemala, funded by the National Science Foundation (BCS 0443820). Fieldwork was completed in 2006. Initial results of the project as of 2003 are reported in Webster et. al. 2004, The Tikal Earthworks Revisited, Occasional Paper in Anthropology No. 28, Dept. of Anthropology, The Pennsylvania State University. A second phase of the project, also supported by NSF, was completed in 2006 and is reported in: Webster, David, Tim Murtha, Jay Silverstein, Horacio Martinez, Richard Terry, Richard Burnett. The Tikal Earthworks Revisited. Journal of Field Archaeology 32 (1): 41-64 (2007).

Richard E. Terry is Professor of Soil Science in the College of Life Sciences at Brigham Young University. His research is focused on soil geochemistry of ancient human activities and vegetative histories of maize agriculture soils in the Maya Lowlands of Mesoamerica. He has had many field projects in Mexico, Guatemala, and Belize. Professor Terry’s NSF grants include “Re-evaluation of the Earthworks at Tikal, Guatemala” (BCS 0443820). Soil analysis work is in progress on “Collaborative Research: Geochemical Detection of Ancient Maya Exchange Environments” (BCS 0919133). Additional samples will be collected at Caracol in February 2012. Sampling is complete and analysis is underway on “Collaborative Research: Uci-Cansahcab Regional Integration Project” (BCS 1064570).
8.0 References


hydrology: Implications for paleoclimatic interpretation of lacustrine δ18O records: Journal of Paleolimnology.


