Collaborative Research: (AOC) Development and resilience of complex socioeconomic systems: A theoretical model and case study from the Maya Lowlands, *PI*: Douglas J. Kennett; *Lead Institution*: Univ. of Oregon; *Collaborating Institutions:* Belize Inst. of Archaeology, Univ. of New Mexico, Univ. of South Florida, Univ. of Southern California, Univ. of California, Davis

Funds totaling $1,220,652 (3 years, 6 institutions) are requested to: (1) develop an integrated multivariate human-landscape-climate model for the emergence and resilience of complex socioeconomic systems and (2) apply and test the predictions of the model with extant data and strategic interdisciplinary research in the tropical Maya lowlands of southern Belize. Highly integrated socioeconomic and political systems marked by administrative hierarchies and rulers developed in ***multiple locations*** around the world during the last 8000 years. The process was episodic and marked by frequent economic failure and political disintegration, in some instances in the context of abrupt climate change. The dynamic socioecological processes guiding economic and political evolution are multivariate and poorly understood. *Analysis requires a* ***computational modeling*** *approach, guided by appropriate theory, paleoenvironmental, archaeological and ethnographic research for ground truthing, and* ***testing*.** Our primary objective is to model dynamic human behavioral responses to environmental transformation, abrupt or gradual, linking these processes to patterns of settlement, resource exploitation, agricultural intensification, competition, and polity stability. To accomplish this we apply a theoretical framework drawn from behavioral ecology that integrates key variables: population density and distribution, environmental suitability as a function of economic intensification and endogenous environmental change, and political exploitation. A secondary goal is to test this model at Uxbenká, a Maya polity that formed in southern Belize between 4000-1500 BP. Archaeological work in the region suggests that increasingly integrated socioeconomic systems formed in the context of demographic expansion, political fissioning, agricultural intensification, and environmental degradation. The available paleoclimatic data also suggest that an abrupt decrease in rainfall played a role in the disintegration of certain polities between 2100-1800 BP that was followed by the reintegration and proliferation of higher order socioeconomic systems after 1800 BP. Many of these systems collapsed completely at 1000 BP, again within the context of abrupt climate change. Extant data from a century of research in this region, complemented with strategic paleoenvironmental, archaeological, and ethnographic work in southern Belize, will guide our statistical evaluation of functional relationships, choice of model parameters and help test model outcomes. A graphical modeling approach will be used to analyze multiple variables to determine their relative influence in the Maya case.

Intellectual Merit: Global climate change is emerging as one of the largest policy issues of this Century. Climatic variability on multiple timescales can elicit a range of human responses depending upon the distribution and density of human populations, modes of production employed, population dependent anthropogenic environmental effects (e.g., deforestation, erosion), the degree of individual integration into higher order political entities, and the degree of economic and political control of populations via coercion or ideological manipulation by administrative hierarchies. Theoretically derived general models capable of incorporating these complex interactions are essential for exploring the stability and vulnerability of higher order socioeconomic systems, including our own. We propose that models adapted from behavioral ecology, implemented through functional system relationships (environment, economy, polity), and confirmed with graphical modeling techniques on archaeological and ethnographic data from the Maya lowlands, will provide models of general importance well beyond the region and time period we investigate. Southern Belize provides a well-researched environmental and cultural context ideal for the inter-disciplinary empirical study necessary to build and test them.

Broader Impacts: Climate change in the context of human-induced environmental degradation is an acute problem facing our increasingly inter-dependent global community of nearly six billion. Current evidence indicates that the societal impacts of rapid climate change need to be assessed in order to develop effective responses. Along with academic publications, our research team is committed to developing education modules for primary and secondary schools in the U.S and Belize, providing teacher workshops and community outreach for sustainable development, and offering project-based interdisciplinary experiences for university students in the US and Belize.

PROJECT DESCRIPTION

CENTRAL RESEARCH QUESTION: Highly integrated socioeconomic and political systems marked by administrative hierarchies and rulers with significant power developed in multiple locations around the world during the Middle and Late Holocene (8,000 cal yrs BP to present, e.g., Adams 2000; Algaze 2001; Blanton et al. 1993; Feinman 2000; Feinman and Manzanilla 2000; Flannery 1998; Kennett and Kennett 2006; Marcus and Feinman 1998; Pollock 1999; Rothman 2004; Tainter 1988; Yoffee 2005; Yoffee and Cowgill 1988). These polities amplified institutionalized intra-group differences in status and wealth that developed ~13,000 years ago, well after the first evidence for anatomically modern humans in Africa (~150,000 years ago) and their subsequent spread throughout the Old and New Worlds (Klein 2004). Archaeological evidence suggests that for the majority of human history groups remained small, occupied relatively large territories at low densities, and moved periodically to adapt to spatial and temporal fluctuations in resources. Group fissioning, environmental infilling, and emigration to diverse habitats were favored over localized increases in group size and density or other forms of economic intensification. Under these conditions complex socioeconomic systems rarely emerged. The development of agricultural economies in multiple independent centers established new human-landscape-climate interactions, fundamentally changing the environmental and cultural history of our planet (Blake et al. 1992; Childe 1951; Dincauze 2000; Flannery 1972; Kennett et al. 2006a; Price and Gebauer 1995; Redman 1999; Roberts 1998; Smith 1998). Intensive food production and associated surpluses also fueled the development of socially stratified, politically centralized, and technologically innovative state-level societies (Nichols and Charlton 1997; Zeder 1991).

We are particularly interested in the observation that the alternating process of societal fragmentation and reintegration fosters the emergence of increasingly complex socioeconomic structures (Willey 1991). Broad patterns of political integration and decline are well documented in the rise of civilization in Mesopotamia, China, Mesoamerica, and South America (Caldararo 2004, Dillehay and Kolata 2004; Schwartz and Nichols 2006; Webster 2002, Weiss 1997). Periods of rapid population aggregation, regional integration, and increased centralized authority are often followed by population dispersal, regionalization, and decentralization. Sometimes this process terminates in the complete regional collapse of integrative socioeconomic systems (Tainter 1998). Oliver-Smith (1998) has argued that disasters (earthquakes, drought) may damage physical facilities or organizational capacities, causing societal collapse. Abrupt climate change also plays a major role in certain cases (Issar 1995; Weiss 1997; Weiss et al. 1993). However, in other cases short term socioeconomic disintegration and regionalization is followed by the development of larger complex sociopolitical structures and more powerful leaders (Willey 1991). This process is visible in the Maya lowlands of Mesoamerica where cyclical patterns of socioeconomic integration are punctuated by periodic societal fragmentation, resulting ultimately in the emergence of Classic Period civilization (1750-1200 BP) characterized by large interacting urban polities, dynastic texts carved in stone, and monumental temples and palaces for ruling elites. An abrupt decrease in rainfall is argued to be one of several contributing factors in the broadscale demise of these interacting polities at the end of the Classic Period (Gill 2000; Hodell et al. 1995; Haug et al. 2003). Decreases in rainfall also appear to correspond with the emergence of these same systems during the transition from the Late Formative to Early Classic Periods (~2000-1750 BP; Webster et al. 2007). The socioecological processes leading to the **emergence** and **resilience** of complex polities are complex and multivariate. ***These complexities are poorly understood and require an integrated modeling approach with appropriate archaeological, ethnographic, and paleoenvironmental calibration and testing***.

CONCEPTUAL MODEL: Our conceptual model of **societal development** and **resilience** considers the dynamic interactions among climatic variations, landscape alterations, human decision-making, and socioecological change. Central to this modeling effort are the ***complex ecosystemic dynamics*** of sociopolitical sustainability within the context of expanding human populations and associated economic intensification. The diversity and resilience of biotic systems and the sensitivity of these systems to climatic or anthropogenic environmental change are interrelated with these broader societal questions. We

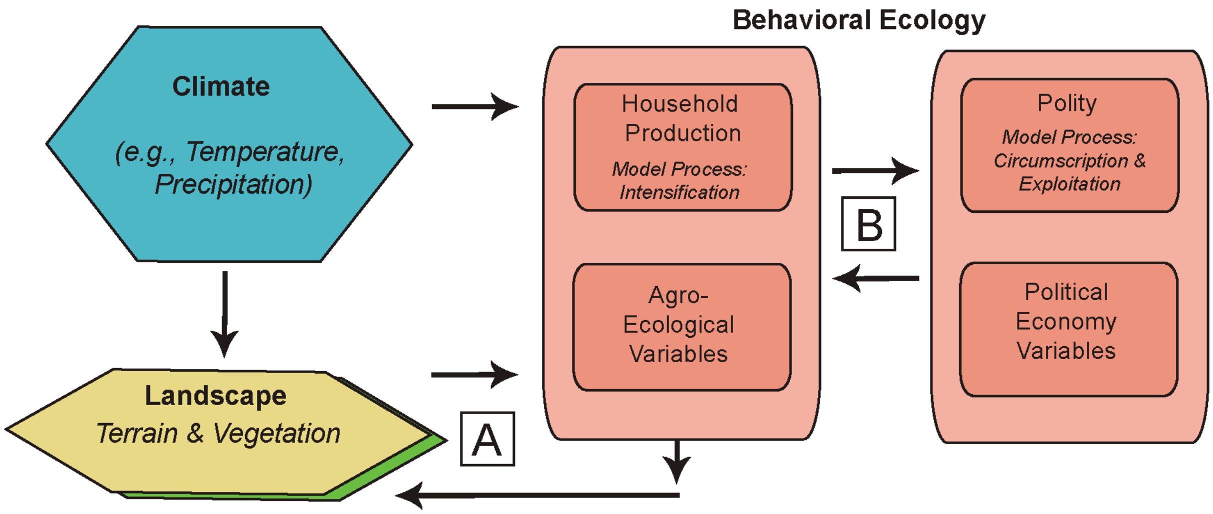

Figure 1. Conceptual model where **A** and **B** represent a constellation of reciprocal linkages: **A** represents landscape interactions; **B** represents political ecological interactions. Using the concepts of agricultural intensification, in-fill and circumscription, we envision a behavioral ecological transition that begins with positive Allee effects (economies of scale to expanding polities) and develops into a situation of declining suitability and increasing exploitation (see Figure 2). The focal locus of causation moves from **A** to **B**, to a coupled interaction of **A** & **B**, each represented by included variables. We anticipate using graphical modeling techniques (e.g., path analysis) to sort out the importance of key variables in each of these categories (see Figure 3).

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propose to develop a general model with three interdependent components; a **dynamic climate component**, a **geospatial terrain and vegetation component** and **a behavioral ecological component** (Figure 1). We will create a transferable modeling environment that can be linked with archaeological and paleoenvironmental data to generate testable hypotheses to be evaluated statistically (see hypothesis formulation and testing, below). Models of societal development are commonly presented in narrative form (e.g., Weiss et al. 1993, Webster 2002), a risky approach given that it is hard to discern without formal modeling if they are dynamically sufficient (Turchin 2003). We build upon and test these narratives in the Maya region with an explicitly quantitative and dynamic modeling approach.

***Dynamic Climate Component*:** The climate component is essential for defining temporal and spatial variability in the overall modeling environment. We will develop multiple time-series ensembles of basic surface-climate variables (e.g., temperature and precipitation), as well as bioclimatic variables such as growing degree-days and moisture-deficit measures directly relevant to agriculture (see Lee et al. 2006). We will use two approaches: 1) the analysis of paleoclimatic simulations, and 2) the construction of modern analogs using extant paleoenvironmental reconstructions and new climatic data generated by this project. The first approach employs traditional "snapshot" simulations (e.g., Otto-Bliesner et al. 2003) and the emerging "Holocene transient" simulations (e.g., the CCSM Paleoclimatic Working Group b30.108 simulations, Otto Bliesner et al. 2006). Output from course-resolution General Circulation Models (GCMs) are downscaled and used to create the necessary time series. In the second approach present-day "reanalysis" (e.g., Kistler et al. 2001, Mesinger et al. 2006) and surface-climate data sets (New et al. 2000) are used to describe the large-scale climatic controls and surface-climate responses for extreme cases defined using climate-mode indices (e.g., the Southern Oscillation Index [SOI] index that characterizes El Niño Southern Oscillation [ENSO] variations), or the "signals" extracted from local climatic records (Shinker et al. 2006; Whitlock et al. 2006). Harrison et al. (2003) provide a mid-Holocene North American example combining both approaches.

Geospatial terrain and vegetation component: The geospatial outcomes of the climatic component will be articulated with a dynamic terrain and vegetation model to provide snapshots of environmental change through time. We employ widely accepted and standard proxy data and interpretive methods for reconstructing biophysical and cultural features of ancient landscapes (Miksicek 1987, Waters 1992, Birkeland 1999). Anthropogenic alterations to the vegetation (e.g., deforestation) and terrain (e.g., erosion) will be incorporated, based on extant archaeological data augmented by selective empirical work in southern Belize (see Data Sources for Model Building). Basic geographic parameters (e.g., latitude, meteorology) combined with local topography (e.g., elevation, slope, and aspect) and geology (volcanic, sedimentary) provide the foundation for understanding the distribution of biotic communities. Depending upon the mode of production (e.g., foraging or farming), humans "map on" to the spatial distributions of plant and animal populations, often in predictable ways (Kennett et al. 2006). Suitable settlement locations are determined by availability of drinking water (rivers or springs), well drained and dry land for dwellings, and wood for fuel and construction. Hunters and gatherers favor environments that are either diverse or rich in specific resources (e.g., coastal locations); farmers are more likely to be attracted to rich and well-watered alluvial soils. Changes in climate alter vegetation cover by promoting or suppressing the distribution of certain species and related biota. Fire regimes are controlled by changes in precipitation and temperature, human settlement and economic practices (e.g., forest clearance for agriculture). Simulation of changing biophysical and cultural features of ancient landscapes is essential for studying human decision-making within the dynamic socioecological processes of societal development and resilience to anthropogenic or climate driven environmental change.

Geospatial databases (Geographic Information Systems [GIS]) provide a well-developed platform to explore these dynamic interrelationships (Hancock & Willgoose 2002; Mitasova & Mitas 2001). We will use geospatial process modeling to reconstruct initial vegetation and terrain, prior to anthropogenic modifications and subsequent dynamics. Landscape evolution resulting from geomorphic processes (e.g., erosion, sediment transport) will be modeled based on fundamental relationships between vegetation cover, climatic conditions, and topography (Hancock et al. 2002; Tucker et al. 2001). Holocene climate dynamics on multiple temporal scales affect vegetation communities and terrain morphology via colluvial and fluvial processes (Mitas & Mitasova 1998). Landscape dynamics will be modeled using geospatial techniques that combine our climate model and anthropogenic behavioral ecology factors based on stochastic rule-based modeling representing human land use. Snapshots of vegetation change and landscape transformation via erosion and deposition will be generated at 25-year intervals. This exceeds the resolution feasible in most prehistoric sequences (see datasets available in Maya test case below). The results of this simulation will be important for assessing both anthropogenic and non-anthropogenic alterations of the vegetation and terrain.

Behavioral Ecological Component. The dynamics of human decision making will be modeled within the framework of human behavioral ecology (HBE; Kennett and Winterhalder 2006; Winterhalder 2002; Winterhalder and Smith 2000), a relatively new field integrating a variety of behavioral, sociopolitical, and environmental variables influencing the emergence, stability and collapse of socio-economic systems. We will adapt the Ideal Free Distribution (IFD), and related Ideal Despotic Distribution (IDD; Fretwell and Lucas 1970) models, to examine interactions among land use, effects of resource exploitation, and the biogeographic distribution and productivity of human populations. Settlement locations or habitats are ranked by their suitability, a quality measure related to the overall productivity of the resource patch and, by extension, the fitness of the initial occupants (Figure 2; also see Winterhalder and Kennett 2006). Habitat suitability is density dependent; it declines with increasing population density. The model predicts that colonizing people will locate first in the best habitats available. As population grows, suitability in this habitat drops due to density-dependent resource depletion or interference arising from competition. When suitability is diminished to a level equal to that of the second ranked resource patch, further population growth will be divided between them. Individuals relocate to their advantage, reaching an equilibrium distribution of population over habitats. When marginal suitability is equal, no individual has an ecological or economic incentive to relocate. Especially important for our analytical purposes, the model allows for economies of scale (Allee effects), producing a variety of interesting non-linear consequences (Figure 2; see Kennett et al 2006b). It is especially adept at moving from assumptions about individual- level behavior to population-level consequences (Sutherland 1996). Variations on the same

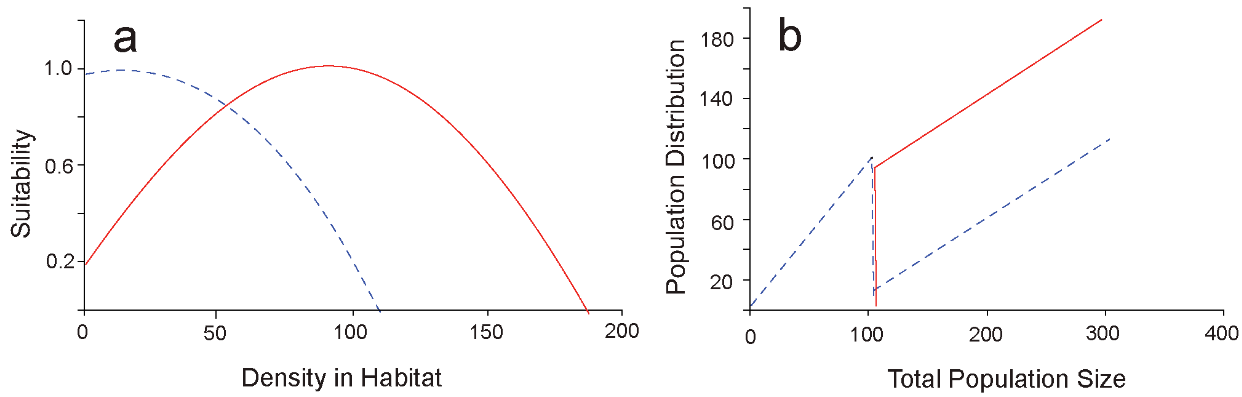

Figure 2. The ideal free distribution (IFD) model determines the equilibrium distribution of populations over habitats (or spatially separable production opportunities), as a function of density and density-dependent suitability. The ideal despotic distribution (IDD) is similar but allows for territoriality or other forms of resource defense. This example depicts the IFD and two habitats. (a) Suitability in the highest ranked habitat declines monotonically with population growth; suitability in the second-ranked habitat, first increases due to economies of scale (Allee effect) and then declines. (b) Individuals populate the highest ranked habitat until its marginal suitability drops to the level for entry into the second-ranked habitat. There is then a rapid migration from first to second habitat, depopulating one and filling the other, until their marginal suitabilities again equalize and further growth is divided between them. We have chosen this form of the IFD to illustrate how marginal quantitative change in one variable (e.g., population size) can have qualitative effects on another (e.g., distribution over habitats or production opportunities).

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model can be used to examine the non-linear properties of technological evolution (Bettinger, et al. 2006; Winterhalder and Hale, in prep). Our IFD/IDD analysis builds upon previous work in more simplified island contexts (Kennett et al. 2006b; Kennett et al. i.p.)

Experiments with non-human populations indicate that as population densities increase, organisms can switch from an ideal free to an ideal despotic distribution in which some individuals gain differential control over territory and resources (Humphries et al. 2001). Two of the senior investigators on this proposal (BW and DK) currently are adapting and combining reproductive skew theory (Reeve and Emlen 2000) with the IFD to model this process of social differentiation. We anticipate a predictive and quantitative model of demographic expansion, settlement relocation, group formation and fissioning, declining habitat suitability and, ultimately, the emergence and episodic disintegration of institutionalized social hierarchies (see also Carneiro 1970; Boone 1992). Central to our approach are the costs and benefits that accrue to individuals under different ecological and social conditions and the emergent consequences for population ecology and sociopolitical stability.

We propose that institutionalized social hierarchies are closely tied to group formation, which is highly sensitive to the possibilities that individuals have for emigration in the face of economic hardship, intra-group competition, conflict, and subordination. We hope to predict not just biogeographic properties of landscape use, but also how dominant members of a group will distribute resources to retain subordinate members. We predict that social hierarchies will be favored when alternative settlement locations are not available or economically viable. Reproductive skew theory adds the especially interesting element that dominants can extract more from subordinates to whom they are related (those subordinates gain inclusive fitness benefits from the dominant's success), leading to strategies in which dominants gain allegiance through manipulation of socio-cultural forms of relatedness.

Our model predicts that dominant members of the group are more likely to provide these incentives to subordinates if: (1) additions to the local labor force significantly increase productivity (economies of scale-such as terracing or irrigation); (2) an outside threat requires additional military recruits; (3) emigration to a viable habitat is limited; and, (4) biological or social bonds of relatedness are weak, perhaps as the size of the group grows. An effective leader continually assesses the ability of subordinates to leave and dispenses resources at levels required to maintain or increase group size. This

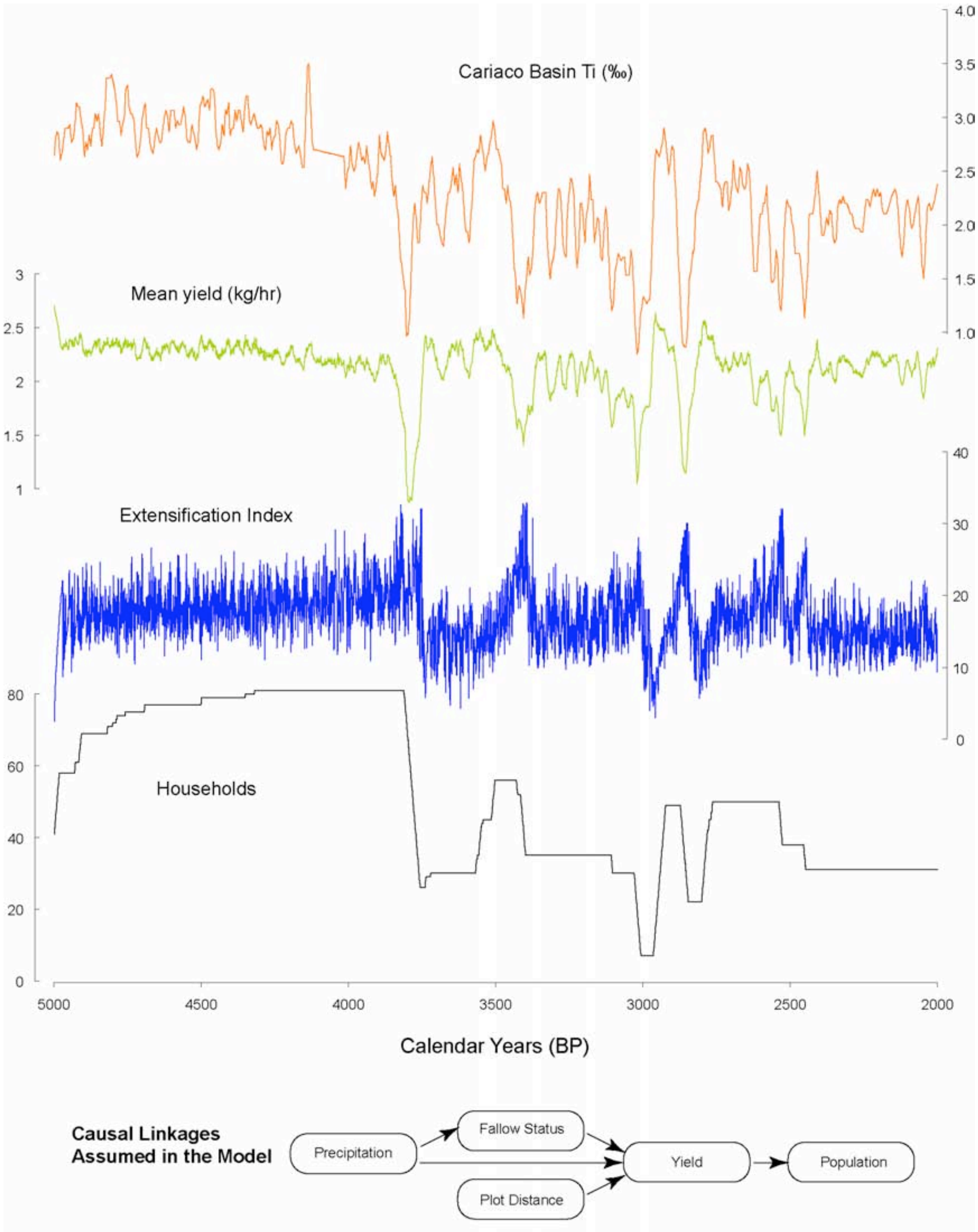

Figure 3. Illustrative example of output from an agent-based landuse simulation linking climate, agricultural productivity, and population, in southern Belize (5000-2000 BP) assuming initial population of 40 households. Plots (2 ha each) around a central village are ranked by potential yield (kg/hr), which accounts for fallow status and distance from the village, and the highest ranked plots are farmed each year. The Cariaco Basin Ti dataset (Haug et al. 2003) is a proxy for precipitation. In the model lower precipitation slows the rate of forest succession in a nonlinear fashion, and hence soil nutrient recovery after clearing. Actual yields are obtained by applying an exponential function related to precipitation to potential yield. Population increases or decreases above or below critical values of mean yield. The extensive index, which can range from 1-34, represents the average distance of cultivated plots from the central village (34=5km). The simulation will be built, tested and retested over the course of the project, with the final version composed of the most robust functional climate-landscape-agroecological-political ecological linkages identified with graphical modeling and the geospatial implementation of the behavioral ecological model using a Geographic Information System. Produced with Interactive Matrix Language programming in SAS 9.1 (SAS Institute 2003).

system ultimately becomes fragile to ecological insult as tensions within and among social groups strain these ties of allegiance. In sum, the IFD/IDD fits the long-term, regional scale of our investigation; its evolutionary ecology origins give it predictive abilities; it can bridge the gap between individual-level behavior (habitat selection) and population-level consequences (exploitation/depletion of resources); it integrates natural (habitat quality) and social (social stratification) phenomena; it examines forms of intensification ranging from habitat selection to technological innovation; and, it predicts non-linear responses under plausible input conditions. There are few limits on what kinds of variables can be accommodated by this model. For instance, climate change might shift the relative suitability (vertical position, thus relative ranking) of habitats or certain habitats/subsistence practices may be more susceptible to density dependent degradation than others. These properties will prove essential for understanding dynamic human-landscape-climate interactions in the development and persistence of complex sociopolitical systems.

Hypothesis Testing: The temporal and spatial aspects of climatic, landscape and socioecological dynamics generated by our observations and modeling efforts will serve as the basis for generating hypotheses to be tested with prehistoric records. Establishing causal connections based on archaeological and paleoenvironmental observations/correlations is challenging. Structured experiments are impossible and many hypotheses are not clearly supported or refuted (Karban and Huntzinger 2006). For example, the interplay among climate change, agricultural productivity and factional competition (e.g., warfare) entails complex processes affecting the development of polities. Causes are not mutually exclusive, but interacting. We must determine to what degree each plays a role and in what configuration of relationships. How important is climatically driven environmental change ***relative*** to decreasing agricultural productivity and the development of inter-village competition and warfare?

We will use ***graphical modeling techniques*** to evaluate multiple working hypotheses of the factor pathways leading to the development of complex polities (e.g., **path analysis**; Shipley 2000; a special case of **structural equation modeling**; Grace 2006; Pugesek et al. 2003). This technique has been developed by ecologists to conceptualize and evaluate causal relationships statistically (Mitchell 2001). Path diagrams represent different cause and effect possibilities (Figure 3; Mitchell 1993) based on first principles, observational data or model output. The strength and sign of individual paths is evaluated using partial regression coefficients. An index of statistical confidence in each model is generated using Bayesian techniques. Available procedures allow for non-linear causal relationships (Scheiner et al. 2000). Using this technique we can rank cause-and-effect scenarios and infer causal processes, assigning probabilities to model variables. Already used to sort out complex variable relationships in studies of natural selection (Scheiner et al. 2000), graphical modeling techniques show great promise for improving our understanding of complex questions like societal development.

DATA SOURCES FOR MODEL BUILDING--THE MAYA CASE: Climatic, landscape and cultural data generated in the Maya region during the last century, augmented with selective field work in southern Belize (Figure 4), will guide our choice of model parameters. Empirical work in southern Belize will involve: (1) generating a precisely dated decadally to annually resolved precipitation record for southern Belize (4000-1500 yrs BP) based on the oxygen isotope values of speleothems (stalagmites) (including several already collected and U/Th dated to this interval); (2) creation of “multi-proxy” lake sediment records of vegetation, fire frequency/intensity, climate change and anthropogenic landscape change (4000-1500 BP); (3) conducting archaeological survey and limited excavations surrounding the pre-Columbian Maya polity Uxbenká, focusing on its early establishment, spatial and temporal expansion of domestic compounds, and surrounding agricultural fields and terraces into areas of varying productivity; and (4) carrying out ethnographic work with present-day Maya people, particularly the Mopan Maya community of Santa Cruz (on whose reservation Uxbenká is located) and the Q’eqchi’ Maya community of San Miguel, to explore the dynamic human responses to ecosystem

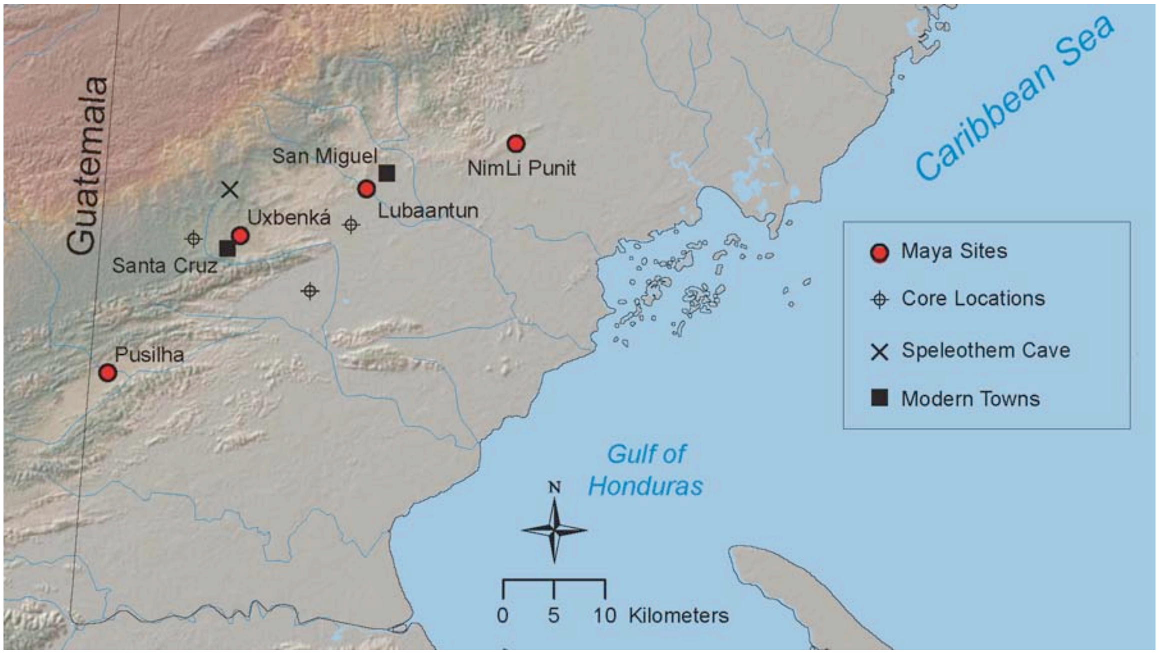

Figure 4. Map of southern Belize showing major prehistoric Maya civic ceremonial centers (archaeological sites) and proposed locations of archaeological, ethnographic, and paleoclimate/environment field research.

change in the same area. The ethnographic study also includes a detailed analysis of contemporary agricultural practices and quantitative experimental work on agricultural productivity, micro-climatology, soils, intensity of land use and local-scale spatial differences (e.g., soil, moisture) in the region.

Southern Belize provides an excellent opportunity in the Maya region to study human-landscape-climate dynamics, because it: (1) contains a rich archaeological record of polity development between 4000-1500 BP, (2) has potential for high-resolution climate and environmental records, and (3) has contemporary Maya populations that are recolonizing the tropical lowland environments surrounding the ancient ruins of former failed polities. The region is also circumscribed geographically and has been difficult to access, now and in the past. To the north it is bounded by inhospitable pine-barrens, to the west by the formidable Maya Mountains, to the south by the swampy Temash and Sarstoon River basins, and to the east by the Caribbean Sea. Polities were smaller in this region compared to the apogee of the Classic Maya world in the central Petén of Guatemala (e.g., Tikal), making it easier to test various model outcomes. Strategic archaeological survey and testing at Uxbenká will provide concise occupation histories, including demographic information and data about changing agricultural practices at different spatial and temporal scales. While human presence in the region extends back further, Uxbenká was the first settled community, occupied as early as 2100 BP. It emerged as a regional center by the Early Classic Period (1750-1500 BP). Carved stone monuments bracket the rise and fall of dynastic political groups and their connections with larger polities outside of southern Belize through 1100 BP when the region went into decline. Speleothems from nearby caves and sediments from adjacent wetlands contain records of local climate change that can be integrated into broader-scale climate series and correlated with local cultural and landscape transformations. Sedimentation records will potentially reveal landscape transformation (e.g., deforestation and erosion) associated with changing agricultural practices. Empirical field and laboratory studies will be combined with extant climatic, landscape and cultural data to set model parameters and test specific model-driven hypotheses.

Extant Climate Data: Available regional paleoclimate records indicate that the Atlantic Intertropical Convergence Zone (ITCZ) migrated south during the middle and late Holocene due to the precessional component of the Earth's orbit (Figure 5). This decreased moisture transport to the Maya region (Brenner

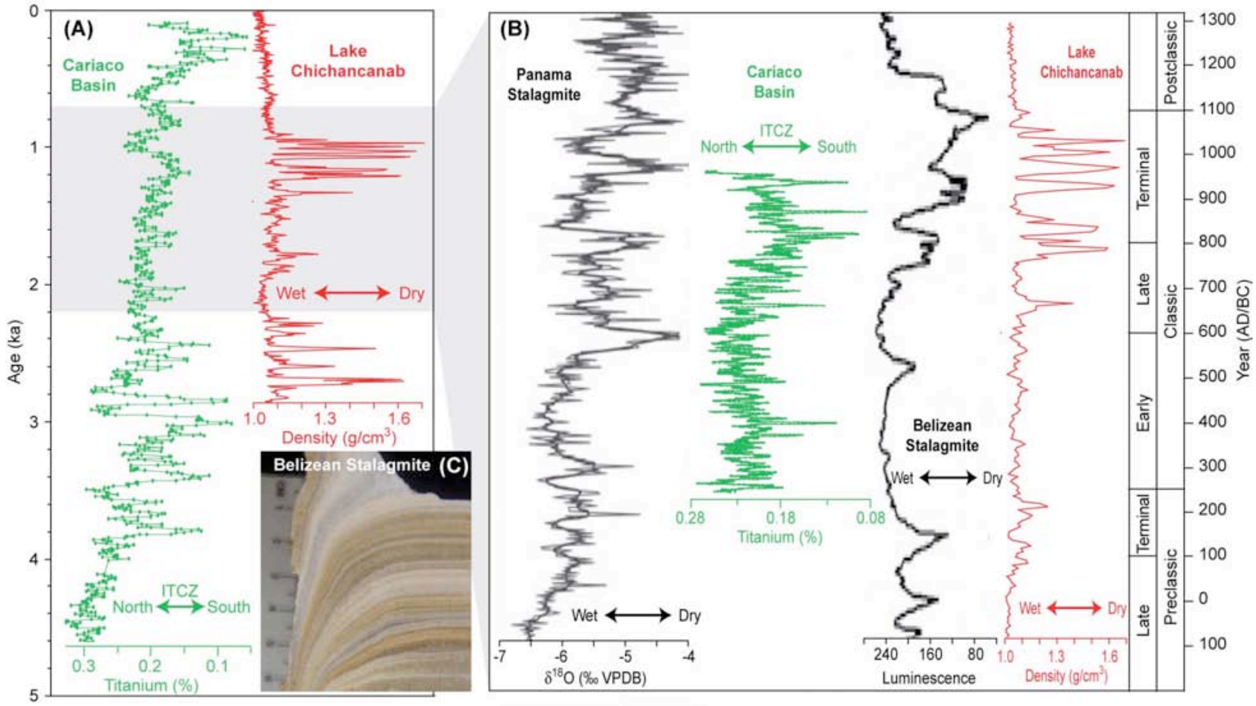

Figure 5. Some of the best available climate records for the lowland Maya region (A) Long-term southward shift of the ITCZ inferred from Cariaco Basin titanium record (green) (Haug et al. 2001; Haug et al. 2003) as well as centennial-scale variations in the mean position of the ITCZ and a measures of drought conditions (red) on the Yucatan Peninsula (Hodell et al. 2005a). Note the general centennial-scale correspondence between the two. (B) Same as (A) but focusing on the ~1500 year interval during which Mayan polities culminated and disintegrated during the Classic and Terminal Classic Periods and including two high-resolution records of precipitation variations inferred from a stalagmites (Panama, Lachniet et al. 2004 and Western Belize, Webster et al. 2007). Note that the offset in timing of brief drought events may result from chronological errors and/or differences in the local climates of these locations. (C) Example of Belizean stalagmite collected from Yok Balum Cave. Fine-scale layers are likely annual and broader-scale color variations are probably interdecadal.

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et al. 2002; Haug et al. 2001). The majority of the best Maya paleoclimate records come from lake sediments on the Yucatan Peninsula (Brenner et al. 2002). Those from lakes Chichancanab (Hodell et al. 1995, 2001) and Punta Laguna (Curtis et al. 1996) appear to be the most robust (Hodell et al. 2005a). Other lacustrine records from northwest Yucatan (Hodell et al. 2005b) and the southern Maya lowlands (Curtis et al. 1998; Rosenmeier et al. 2002a) appear compromised by climatically unrelated changes in hydrology (Hodell et al. 2005a) and anthropogenic deforestation (Rosenmeier et al. 2002b), respectively.

Sediment cores taken from Lake Chichancanab exhibit discrete intervals of interbedded gypsum and organic-rich strata indicating generally dry phases punctuated by wetter conditions (Hodell et al. 2005a). The oldest of these dry phases (~2000 BP) appears to correlate with a southward shift of the Atlantic ITCZ inferred from the Cariaco Basin titanium record (Haug et al. 2001). Although the deep lake cores do not extend further back than this, the Cariaco record suggests that the interval between 4000 and 2000 BP experienced large shifts in the latitude of the Atlantic ITCZ on millennial to interdecadal timescales, which would have affected moisture transport to the Maya world. Between ~2000 and ~1500 BP the Yucatan lake records and Cariaco record indicate a generally wetter phase and a more northern Atlantic ITCZ. Both of these records (Haug et al. 2003; Hodell et al. 2001; Hodell et al. 2005a) and stalagmite data from Panama (Lachniet et al. 2004) and central western Belize (Webster et al. 2007) indicate a dry interval towards the end of the Preclassic (~1800 BP) when several polities disintegrated.

The most detailed Maya paleoclimate reconstructions have focused on the Late to Terminal Classic Periods. The Lake Chichancanab records indicate three dry phases (1300-1270 BP, 1180-1080 BP, 1030-850 BP), punctuated by wetter conditions (Hodell et al. 2005a). There are indications that these wet/dry oscillations were cyclic at centennial and interdecadal frequencies and possibly paced by variations in solar irradiance (Hodell et al. 2001). The high-resolution titanium record from Cariaco Basin (Haug et al.

2003) is supportive, indicating a dry phase during the Terminal Classic Period. Superimposed on this trend are interdecadal wet/dry oscillations that appear to match the frequency found in the lake cores (Hodell et al. 2005a). The recently published Belize stalagmite record indicates drought conditions during the Classic Period "hiatus" and the collapse (Webster et al. 2007). Similarly, the Panamanian stalagmite record also appears to exhibit these same dry/wet phases possibly related to variations in the frequency of El Niño events (Lachniet et al. 2004).

Additional and more precise data are needed to better model human-landscape-climate interactions. For example, the calibrated radiocarbon dates used for the chronology of the lake sediment records have errors on the order of ±90 to 130 yrs (Hodell et al. 2005a) preventing accurate correlation to cultural events. The Cariaco record does have a floating annually counted varve chronology anchored (1020 BP) by correlation to the onset of the Medieval Climate Anomaly. However, it is distant from our study area. We have identified and sampled stalagmites from southern Belize. Preliminary work indicates that these data will help to refine the climatic component of our modeling effort by providing a well-dated precipitation record for the local region between 4000 and 1500 yrs BP.

Proposed Climate Reconstruction from Tropical Speleothems: Strong vertical convection is the primary source of precipitation in the tropics; the oxygen isotope ($\delta^{18}O$) values of rainwater are inversely correlated with the amount of rainfall (Rozanski et al. 1993). This signal is carried from rainwater to groundwater to cave dripwater and preserved in the $\delta^{18}O$ of speleothem calcite (McDermott 2004). Thus, by sectioning a stalagmite along growth horizons and determining the $\delta^{18}O$ values of samples, a high-resolution record of past rainfall can be generated (e.g., Fleitmann et al. 2003; Neff et al. 2001; Wang et al. 2001). Annual layer counting is possible when laminations are preserved, matched to a very precise radiometric chronology (±20 yr) when detrital thorium content is low. Cave-environment and kinetic effects are minimized by selecting stalagmites from deep within caves where temperature is stable and relative humidity high. Although changes in the drip rate can affect stalagmite $\delta^{18}O$ values, this drives them in the same direction as the amount effect such that wetter conditions result in more negative $\delta^{18}O$ values (Burns et al. 2002; Fleitmann et al. 2003). Equilibrium calcite deposition can be determined for the modern cave environment by analyzing active dripwater and calcite formation (Mickler et al. 2004).

Although a more complex system than that described above, the carbon isotope ($\delta^{13}C$) values of speleothem calcite may also be used to reconstruct past climate as well as human impacts on the region. The $\delta^{13}C$ values of speleothem calcite are related to the $\delta^{13}C$ of soil CO_2, mixing of soil CO_2 with bedrock CO_2 in the groundwater, and CO_2 degassing in the cave (McDermott 2004). Changes in the overlying vegetation tend to drive the $\delta^{13}C$ signal with cooler/wetter (warmer/dryer) conditions resulting in lighter values (heavier values). Carbon isotope values in a stalagmite from Belize record El Niño events, most likely through changes in local rates of soil respiration and ecosystem CO_2 recycling (Frappier et al. 2002). Carbon isotope values may also indicate changes in local slash-and-burn agriculture (Lachniet et al. in preparation).

The uranium series method, based on the decay of ^{234}U to ^{230}Th, is an ideal chronometer for dating speleothems (please see facilities section for lab set-up and procedures). With the introduction of multi-collector inductively coupled magnetic analyzer mass spectrometers (MC-ICPMS) with multiple ion counters, we are now able to produce extremely precise age estimates (Asmerom et al. 2006) from a much higher ionization efficiency of Th (by up to a factor of 100), compared to thermal ionization mass spectrometers. We are now working with a new Thermo Neptune MC-ICPMS, using a method that we developed that utilizes a combination of Faraday cups with 10^{10}, 10^{11} and 10^{12} Ω resistors, an electron multiplier and a channeltron (Asmerom et al., 2006).

In June 2006, we collected 10 stalagmites from Yok Balum, a cave 2 km from Uxbenká. Temperature and humidity data loggers were installed in the cave, along with apparatuses to collect modern calcite deposition. Monthly rainwater and cave dripwater collection was initiated. We have obtained preliminary age data from these speleothems. Several have low detrital thorium, making them suitable for accurate dating by the U-series method, and have ages that cover the period between 4000 and

1500 BP and the present. During Year 1 weather stations will be set up near this cave so that modern climate data can be collected to calibrate the climate proxies along with other nearby instrumental climate records. The best stalagmite specimens will be selected to generate stalagmite paleoclimate records, including oxygen and carbon isotope analyses (decadal resolution from 4000-1500 BP). Several "windows" at annual resolution will also be generated.

Extant Landscape Data: Landscapes in the Maya region reflect millenia of decision-making processes concerning land use in the face of changing modes of agricultural production, demographic pressure, local micro-environmental conditions, and climatic change (Alsselmetti et al. 2007; Denevan 1992; Dunning 1996; Dunning and Beach 2000; Fedick 1996a; Fedick and Ford 1990; Wingard 1996). Forest clearance using fire was and continues to be an effective, labor-saving component of Mayan subsistence. Changing charcoal abundance in lake and wetland cores indicate the intensity of forest burning throughout the Holocene. Increased fire frequency in the Maya lowlands at the beginning of the Late Holocene (~4000 BP) correlates with pollen spectra showing increases in domesticates (*Zea* sp., *Manihot* sp.), disturbance sensitive taxa (e.g., Graminaea, Cyperacea) and declines in primary forest arboreal taxa (e.g., Moracaea, Urticacaea, Bursuraceae) (Piperno and Pearsall 1998). Increasing soil erosion exhibited in lake records during this period in the Petén (Guatemala) and the Yucatan (Mexico) suggests the emergence of long-fallow swidden agriculture in upland areas made feasible by the dryer Late Holocene climate (Piperno and Pearsall 1998; Rosenmeier et al. 2002a, 2002b). By 3500 BP, regional adaptations to wetland agriculture became important in the lowland swamps of northern Belize. Early research suggested extensive raised fields in Guatemala (Adams 1980, Adams et al. 1981) and northern Belize (Harrison 1993, 1996; Puleston 1978; Turner and Harrison 1983) dating primarily to the Late Classic Period (1500-1200 BP). Later work has shown that many of these are either natural landforms that were never cultivated, or they are fields drained by ditching during the Preclassic period (~3000 BP) (Dunning et al. 1991; Dunning 1996; Pohl and Bloom 1996; Pohl et al. 1996; Pope et al. 1996). Drained fields on Albion Island, and in Douglas, Cobweb, and Pulltrouser swamps appear to have been completely inundated and abandoned by ~2200 BP due to a rising water table (Pohl et al. 1996).

Landscape alteration intensified in the Maya uplands after ~3000 BP, as population pressure forced a shift to short-fallow agriculture, putting more land and less favorable hillslopes under cultivation. Buried topsoils dating to 3500 BP at La Milpa and Petexbatun indicate that soil instability and sedimentation rates increased in response to agricultural intensification during the Middle to Late Preclassic (2900-1500 BP; Dunning and Beach 2000; Dunning et al. 1999). In the Petén lake records, inorganic sediment and charcoal abundance track a shift to short-fallow slash and burn agriculture superimposed on the signal of drier climate through the Late Holocene, demonstrating complex linkages between human alterations, vegetative cover, and geomorphic stability (Binford et al. 1987; Curtis et al. 1998; Hodell 1995, 2000; Rice 1993; Rosenmeier et al. 2002a, 2002b). Behavioral responses to environmental degradation during the Preclassic to Early Classic involved decentralization or out-migration. Soil retention structures (e.g., terraces, check dams) do not appear to have been employed during this period (Dunning and Beach 2000).

New polities were established during the Classic Period (1750-1200 BP) as agricultural practices intensified against a backdrop of growing population and increasingly dry and erratic climate (Haug et al. 2003; Hodell et al. 1995, 2000). Diverse human responses are evident, illustrating the complexity of Classic Mayan political disintegration. In the Copán Valley, cultivation spread from productive valley floor "pockets" onto hillslopes, overtaxing productive capacity and undermining the geomorphic stability of the soils (Abrams and Rue 1988; Webster et al. 2000; Wingard 1996). Prolonged drought episodes during the Late and Terminal Classic (1500-1200 BP) further decreased vegetative cover, exacerbating anthropogenic erosion and culminating in landslides that buried the city center ~2 m of colluvium (Abrams and Rue 1988; Fash and Sharer 1991; Webster et al. 2000; Wingard 1996). In the Petén and Yucatan, lake cores show a similar mass-wasting event (the "Maya clay" (Binford et al. 1987; Deevey et al. 1979; Hodell et al. 1995, 2000). In northern Belize the Preclassic drained fields are capped by an analogous stratum (Pohl and Bloom 1996; Pohl et al. 1996; Pope et al. 1996). Centers in the vicinity of

Petexbatun, in contrast, show no evidence of increased erosion during this period, despite intensive cropping and continual forest suppression seen in pollen records (Demarest 2006; Dunning 1996; Dunning and Beach 2000; Dunning et al. 1998). Sophisticated conservation measures included terraces, check dams, and reservoirs in the Petexbatun and at La Milpa, and Tamarindito. The elaborately terraced landscapes around Caracól are another example of soil conservation in the face of intensive cultivation (Chase and Chase 1998). Multiple land use strategies, conservative and otherwise, were employed up to the Terminal Classic (1200-1000 BP) to mitigate the effects of anthropogenic landscape alteration (Fedick 1996b, 1996c; Fedick and Ford 1990; Dunning 1996; Dunning and Beach 2000). Given the array of local factors informing these decisions, studies of landscape transformation 4000-1500 BP must be focused on social and natural processes that operate on regional and smaller scales. Simple extrapolations from one region's landscape history to another's will be inadequate (Fedick 1996b, 1996c; Fedick and Ford 1990; Dunning 1996).

Proposed Landscape/Environmental Study: We propose to augment extant environmental datasets to model coupled human-landscape interactions in the Maya region by obtaining long-term fire and vegetation histories from lake sediments in southern Belize. Charcoal, introduced to a lake or wetland during and shortly after a fire, provides information on fire frequency and intensity. Reconstructions of fossil pollen registers long-term changes in vegetation, as well as post-fire succession. High-resolution, macroscopic charcoal analysis (particles >125 μm) can detail the temporal and spatial variations in local fire regimes on decadal to millennial times scales.

Sediment cores will be obtained from three wetlands using a hand-held 5-cm-diameter modified Livingstone sampler. Core segments will be extruded and described in the field, wrapped in cellophane and aluminum foil, and transported to the Oregon paleoecology lab. Each core will be sliced longitudinally, described, and subsampled for charcoal, pollen, phytoliths, microfauna (ostracods), magnetic susceptibility, and loss-on-ignition analysis. During a pilot study in 2006 we extracted two cores from the region that show promise for developing these long-term records.

Macroscopic charcoal analysis will be undertaken to reconstruct the fire history of each site between 4000 and 1500 years ago. Only charcoal particles >125 μm will be counted in this study because recent research has shown that these particles are not transported long distances (Clark and Patterson 1997; Gardner and Whitlock 2001; Millspaugh and Whitlock 1995). Methods will follow Long et al. (1998) and Whitlock and Larsen (2001). Abundance (particles/sample) will be converted to concentrations (particles/cm^3). This time series will then be separated into two components, background and peaks, using statistical programs (CHAPS, P. Bartlein, unpublished). Peaks that exceed the background value by a preset threshold ratio will be interpreted as a fire episode. A fire frequency curve will be plotted against the age of the core and changes in the fire frequency analyzed.

Pollen analysis will be undertaken to reconstruct vegetation history between 4000 and 1500 yrs BP, following standard techniques described in Faegri et al. (1989). Analytical intervals will vary depending upon the sedimentation rate and age of each core. In general, sites that cover this time interval will be sampled at approximately every 50-100 years; 300-500 pollen grains will be counted per sample, and an exotic tracer will be added to each sample and counted so that pollen percentage and pollen concentration (grains cm^{-3}) can be calculated. Pollen will be identified to the lowest taxonomic level possible, based on modern phytogeography.

Magnetic-susceptibility analysis will be used to determine clastic material input into each watershed (Thompson and Oldfield 1986) from such events as fire (Gedye et al. 2000), volcanic eruptions, surface runoff, stream flow, and mass movement (Dearing and Flower 1982). Readings will be taken at contiguous 1-cm intervals from either subsampled sediment or intact cores using a Sapphire Instruments magnetic susceptibility sensor. Weight-loss after ignition will be used to determine changes in the amount of organic material in the sediment and will help categorize the productivity of the site at different time periods (Dean 1974). At 5-cm intervals, subsamples of 1 cm^3 will be placed in crucibles and heated for 1 h at 550°C. Loss-on-ignition values will be used to construct an organic content curve (depth versus % organics). Chronological control of the sediment cores will primarily be determined using AMS ^{14}C dating.

Extant Cultural Data. Over a century of archaeological research has been conducted in the tropical Maya lowlands. Patterns of demographic expansion, movement and decline are well studied. They point to complex relationships between political development and disintegration (Culbert and Rice 1990; Demarest 2006; Fash 1986; Hammond 1981; Hansen 2001; O'Mansky and Dunning 2004; Rice and Rice 1990; Rice et al. 2004; Webster 2002; Webster and Freter 1990; Willey 1974). Biotic and landscape effects (e.g., deforestation, erosion, animal diversity) of expanding and contracting populations (e.g., Abrams and Rue 1988; Dunning et al. 1998, 1999; Pohl 1985, Pohl et al. 1996; Webster et al. 2000; Wingard 1996) along with highly varied strategies to combat these impacts and increase agricultural productivity (Dunning and Beach 1994; Fedick 1994, 1996a; Harrison and Turner 1978; Pope and Dahlin 1989; Scarborough 1996) are also known. New paleoclimatic data complicate interpretations of environmental degradation and indicate variability on different time-scales (Curtis et al. 1996; Haug et al. 2003; Hodell et al. 1995, 2001). Bioarchaeological data indicate disease and decreased stature are associated with demographic expansion, environmental change, and agricultural intensification (Storey 1997; Wright 1997, 2004; Wright and White 1996). The dynastic histories of many of the larger Maya polities (e.g. Caracol, Copán, Tikal) are well known from improving decipherment of Maya hieroglyphic texts during the last 20 years (Chase and Chase 2001; Fash and Stuart 1991; Houston 2000; Schele and Freidel 1990; Schele and Mathews 1998; Sharer 2003; Stuart 1992; Stuart 2004; Stuart and Houston 1994). These epigraphic studies provide a wealth of information on historical linkages to states outside the Maya world (e.g, Teotihuacan, central highlands of Mexico; Braswell 2003; Culbert 1991; Marcus 2003; Stuart 2000), including specific information regarding social behavior, political withdrawals, marriages, and warfare between different centers (Ashmore et al. 2004; Chase and Chase 1998; Coe 1988; Freidel 1981, 1986; Freidel and Schele 1988; Houston 1983). Maya archaeology, art, and epigraphy also elucidate aspects of divine kingship, coalition/alliance building, political economy/ exchange, ritual/ideology and the perception of life and death that are not normally discernable in prehistory (Fash 2002; Masson and Freidel 2002; McAnany 1995; Scarborough 1998, 2003; Taube 2004). Caves and cave rituals served as a nexus between religious/political action and the natural environment (Brady 1989; Moyes 2000, 2005; Moyes and Brady 2005; Prufer and Kindon 2005). Our understanding of how elite and non-elite sectors of Maya society articulated is improving (Lohse and Valdez 2004; Yaeger 2003). Prior ethnographic research in the region has documented household variability in decision-making and responses to social and economic change (Wilk 1991 [1997]); Steinberg 1998) as well as transformations in ethnoecological knowledge, home garden composition, and agroecological practices (Zarger 2002a; 2002b). These rich historical and ethnographic data allow contextualization of the model with regards to site-specific human ecology and recorded changes in land use and population mobility, in order to develop and test an integrated model of political development and disintegration in the tropical Maya lowlands of southern Belize. Evaluating patterns of human-environment dynamics across climatic, archaeological, and ethnographic data sets is vital for establishing behavioral parameters within the overall modeling environment.

Proposed Cultural Work: Archaeology-To calibrate our models, refine functional relationships and evaluate our integrated long-term behavioral framework, we will use a combination of climatic modeling and high-resolution paleoclimate/environmental work coupled with strategic archaeological and ethnographic investigations. Regional archaeological data will be augmented with a strategic archaeological study surrounding the ancient Maya city of Uxbenká in southern Belize. This component is critical to our modeling efforts because: (a) published information regarding regional settlements and demography in the Maya region are largely narrative, with few studies providing the necessary quantitative data to characterize population growth and contraction, and (b) southern Belize offers a compelling archaeological region to test our models in that it is spatially bounded, had a continuous occupation history, and was fully integrated with the political economy of the broader Maya world.

Preliminary studies suggest a settlement history consistent with the IFD/IDD model. Though the earliest human impacts in the region are poorly known, human presence in southern Belize dates back to at least 8000 BP (Lohse et al. 2006). By ~2100 BP Uxbenká existed as a small agricultural community, with perishable structures built atop small dirt mounds. It was several centuries before the community emerged as a regional center during the Early Classic Period (1750-1500 BP) as indicated by carved stone monuments that bracket the rise and fall of dynastic political groups and their connections with larger polities outside of southern Belize. Uxbenká's initial rise coincides with Tikal's ascent to power (Laporte 2001; Laporte and Morales 1994; Prufer 2005) during what has been described as a southward expansion of Maya cultural and political traditions (Martin and Grube 2000; Mathews 1985; Sharer 2003: 320, 322). Even during this time, preliminary studies suggest a relatively small population nucleated around the site core. Following 1500 BP settlements appear to have grown as population growth forced expansion into rural areas away from the site core and nearby watercourses. It is also following 1500 BP that regional growth begins. Though Uxbenká was the first Maya polity in southern Belize, in-migration and local fissioning expanded populations across southern Belize during the Late Classic Period (1500-1200 BP) and by the beginning of the Terminal Classic (1100-1000 BP) the regional social fabric was made up of over 70 competing communities including 11 substantial civic-ceremonial centers.

Field activities will focus on (a) establishing a reliable and quantifiable settlement chronology for the Uxbenká polity, and (b) relating that chronology to the spatial growth and development of the site's surrounding agricultural landscapes. Archaeological fieldwork will describe the initial occupation and cycles of growth of Uxbenká spatially and temporally. Chronological control of sediment stratigraphy will be determined primarily using AMS ^{14}C dating while cultural contexts will be dated using a combination of ceramic analysis (Type-Variety), AMS ^{14}C dating, and stratigraphic associations.

We will develop reliable population estimates for different occupation periods, to correlate population changes with landscape modification and agricultural intensification. These goals will require an intensive program of mapping, survey and excavation, of settlement and agricultural areas (approximately 100 km^2) centering on the urban center at Uxbenká. We will focus on landforms where evidence of prehistoric settlement or agriculture is likely to be found, based on soil and topographic maps, aerial and satellite imagery, and the results of previous studies of regional settlement patterns (Hammond 1975; Prufer 2005; Prufer et al. 2006). 100 percent of all architecture constructions, agricultural features and other human modifications to landscapes will be mapped using Trimble GeoXT and Leica GPS units (sub-meter accuracy) and a Leica "Smart" Total Station. This information will then be integrated into a regional GIS. Second, within these survey areas, stratigraphic excavations will be conducted to collect (a) cultural and organic materials to date the occupation sequences of all residential compounds, in order to reconstruct population growth and decline at the household level and (b) soils from a representative sample of agricultural contexts, including field terraces (several have already been identified at Uxbenká), "kitchen garden" contexts between architectural groups, and areas where slope, soils, and drainage suggest agriculture might have been intensively practiced or where it is practiced today. Dating households and agricultural contexts will allow us to track the growth of settlements as they became more dispersed (less nucleated) which we predict would have been simultaneous to the expansion of the urban core in terms of geography and influence. The data should show levels of agricultural intensification (both in terms of labor investment and farming strategies) as elite demands on the population grew. These factors, along with increased population, would have pressured nucleated settlements to break off into household groups, and these newly formed corporate groups would have chosen new locations based on evaluations of soil quality, terrain features, water availability, and distance to the site core.

Ethnography-Climate and landscape intersect with the agro-ecology of household-level food production and, via the political economy of multiple households, on the development and ultimately the disintegration of higher-level political units. Linking climatic, environment and human systems requires we understand the effects of biophysical and sociocultural environments on the efficiency and reliability of subsistence production. Conceptually, we represent this process with functional relationships captured in the IFD/IDD model, assessing habitat and agricultural practices in terms of population density and environmental suitability. Household level efforts to maintain production on advantageous terms under prevailing conditions of climate, habitat, population density and demand for surplus, feed into political economic considerations, stimulating political development and ameliorating or intensifying the stresses that ultimately lead to political collapse and perhaps landscape abandonment. Empirically, we must understand and measure contemporary functional properties of adaptive agro-ecological responses in order to reconstruct past responses in southern Belize. Ethnography complements our archaeological methods in advancing longer-term reconstruction of societal evolution. Climate and environmental change likely played a role in the development and persistence of complex sociopolitical systems, but these variables necessarily act on socio-economic viability through local production decisions of households positioned on a real landscape (Winterhalder and Goland 1997). To understand long-term dynamics, we must know the micro-foundations of the human component; ethnographic study adopting ecological anthropology methods provides us that knowledge (Moran 1995; Balee 2006).

In the primary study community, Santa Cruz, subsistence is provided from maize farming, use of non-cultivated resources, and wage labor opportunities in education, industrial agriculture and aquaculture, and tourism. Over a period of three consecutive years and agricultural cycles we will gather concurrent, quantitative and qualitative datasets on: 1) Household time allocation, in an inclusive set of categories focused on subsistence and household economy, using a low-intrusion, spot-check methodology (Borgerhoff Mulder and Caro 1985); 2) Local micro-climatology, via a network of auto-recording weather stations placed in key agricultural settings that can be linked to yields; 3) Soil quality and its distribution on the landscape in relation to other factors auspicious to production; 4) Input-output features of agricultural production and other uses of the local landscape for subsistence (Hunt 1995); 5) Household economy, including non-farm income and expenditures; and, 6) Ethnoecological perceptions of climate change and weather prediction, habitat quality (including soils), habitat susceptibility to degradation, production risk and response effectiveness. This work will focus on 25 Mopan Maya households, selected randomly from those willing to participate, using standard ethnographic methods of participant observation, informal, and semi-structured interviewing (Bernard 2006).

We will generate ethnographic data on soils, weather and weather prediction, cropping patterns and fallow systems, effects of weather conditions, soils and other input factors on productivity across diverse landscapes, cultivation technologies and cultivars, and means of managing risk. By accumulating three years of data, we should capture enough variability in weather, environment and other factors (e.g., pests) affecting agriculture to calibrate models and determine the configuration of the functional subsystems affecting interpretation of the IFD/IDD. For example, what adjustments are made by different households to late or insufficient rainfall at the beginning of the primary planting season? What are responses to prolonged drought? How are new agro-ecological landscapes chosen when failure of current ones prompts dispersal (e.g. what bio-indicators are used to assess soil quality?). In short, *how do population density, agro-ecological practices and distribution in relation to changing landscapes affect environmental suitability and the IFD/IDD processes we envision as key to prehistory*? Although essential differences between ancient and present-day polities exist (regional vs. globalized states), and contemporary agro-ecological practices do not mirror ancient strategies (current herbicide inputs are quite high), there are overarching similarities in local ecology, maize agriculture, use of non-cultivated species, and weather events (hurricanes, drought). Contemporary response to environmental variables will be essential to our interpretation and modeling of longer-term changes in the past. The aim is to include data on human-environment dynamics at different points in time to inform the model, not to create direct comparison between ancient and 'modern' systems.

In practice we will organize this element of the proposal around three Ph.D. students (two from UC Davis; one from U. South Florida). Each will have responsibility for gathering the common databases mentioned above for a period of one year, while they concurrently pursue a customized individual thesis, the UC Davis students focused on modeling agro-ecological responses and the South Florida student on intergenerational transformations in the agro-ecological system. The kind of functional ecological understanding we seek is gained only from extended, in-depth ethnographic research with the population whose livelihood is intimately tied to this landscape. Familiarity, trust, and collaboration with agroecological experts, educators, and other stakeholders are necessary to complete this component of the project as well as planned educational activities (outlined below). Agroecological responses to climate change and landscape modification are at the heart of our effort to model political evolution in the past. Ethnographic fieldwork provides data of sufficient precision, duration and spatial extent to capture regional processes in southern Belize within a behavioral ecology framework.

EDUCATION ACTIVITIES

We will promote the integration of research and education through: (1) educational outreach to primary and secondary schools in the Mopán Maya community of Santa Cruz and the Q'eqchi' community of San Miguel; (2) establishment of a living-learning agricultural "garden" at the Maya ruins of Uxbenká; (3) creation of interactive exhibits for the associated cultural center; (4) development of problem-focused, inquiry-based curriculum modules (books for students and teachers, linked classroom and garden activities, and CD-ROMs of maps, photos, graphs, etc.) for primary and secondary schools in the United States and Belize; and (5) collaborative partnerships between universities and primary schools in the US and Belize involving undergraduate and graduate students.

1) Maya communities in southern Belize are poor (average household income < $1000 per year) and relatively isolated. We consider educational outreach at the local level to be central to our educational mission. Dr. Rebecca Zarger (South Florida) and Dr. Keith Prufer (New Mexico) have established a strong collaborative relationship with these two Maya communities. Dr. Zarger has nine years of research experience with school children and adolescents in the Toledo district, and has begun working with a group of parents, teachers, the Ministry of Education, and local leaders to integrate local cultural and environmental heritage into curricula. Providing educational materials based on our scientific discoveries is one way that we can give back to local communities. Primary schools in Santa Cruz and San Miguel will pilot the modules. The Julian Cho Technical College, a regional secondary institution, with primarily Maya students, will be asked to participate. Dr. Zarger has already identified teachers interested in working to develop this type of experiential, locally-focused curricula. Our education modules will articulate with exhibits in the developing archaeological park surrounding Uxbenká (see below) and the efforts of the Maya Area Cultural Heritage Initiative (MACHI). Based on previous work, we anticipate the support of the Ministry of Education and the National institute of Culture and History. The Maya modules will form the basis for educational materials for use in the U.S.

2) In order to promote capacity-building and cross-cultural exchange of pedagogical strategies, we will identify an experienced curriculum developer in the U.S., at the Florida Center for Instructional Technology, University of South Florida, in Tampa, Florida, as well as in the Faculty of Education and Arts/Belize Teacher's College, University of Belize. One key aspect of this work will be to hold a three-day long workshop for educators in Belize in year 3 of the project, moving from curriculum planning, to piloting materials, publication, and broader implementation to regional and national schools. Dr. Zarger and the two curriculum developers will direct the workshops and invite officials from the Ministry of Education and the Toledo District Education Office, primary school teachers from Santa Cruz and San Miguel, principals, and representatives of non-government organizations to participate. Curriculum modules that will be piloted, revised, and distributed to the Ministry of Education, the Institute of Archaeology and Institute for Social and Cultural Research, for dissemination within Belize. In the US we will distribute these modules to libraries and cultural institutions (e.g., museums) in our respective communities and provide teacher workshops (see below more specific school relationships).

3) Based on three years of research at the Uxbenká site and in Santa Cruz, Dr. Prufer and Dr. Zarger are proposing a collaborative co-management plan for the Uxbenká archaeological park, involving community members, the newly formed community-based non-government organization "Uchb'enka K'in Ahaw Association" which represents village interests, the Belize Institute of Archaeology, and the Belize National Institute of Culture and History. This is a community-based development project that integrates site reconstruction for educational and tourism purposes, construction of a cultural center, and training of local residents to manage and protect these cultural and environmental heritage resources. This work is well under way with funds from elsewhere. Archaeological parks in the Maya world play a vital

educational role for local communities and large numbers of people from around the world who visit. Uxbenká itself will therefore play a focal role in our educational initiative.

4) We intend to reconstruct one section of an agricultural terrace near the sites' center and, working with local community members, we will also establish a small living garden on this terrace that contains a range of domesticated and wild plants and trees used by both ancient and modern Maya peoples, as documented by Dr. Zarger in 2006. The garden will function as a living "lab" for students and as an activity space for garden-based curricula modules. An associated exhibit in the cultural center will use modern and ancient Maya agricultural practices and local environmental knowledge as a starting point to highlight the interrelated nature of demographic expansion, climate change, landscape transformation, and sociopolitical change. For instance, we intend to provide a polished thin section of a speleothem collected from the nearby cave of Yok Balum showing its incremental growth and the drill holes where samples were extracted for analysis. A parallel graph will show changes in the oxygen isotopic composition and associated rainfall estimates between 4000 and 1500 yrs BP. Similar exhibits will be created for the other environmental records and integrated with sociocultural history with an emphasis on the dynamic nature of these ecosystems.

5) Dr. Zarger is currently working with other faculty at USF, funded by the USF Collaborative for Children and Families, to link educators with interests in garden-based science and social science curricula in the Tampa Bay Garden Network. The modules at the Uxbenka living-learning garden will be tailored for use at Tampa area schools participating in the Network, with the assistance of the curriculum developer at USF. Partner schools in Tampa will be selected for the primary schools in Santa Cruz and San Miguel so that teachers and students may exchange ideas and experiences related to garden-based curricula. Gardens are especially useful for bringing knowledge and skills of local community members into environmental education (Keifer & Martin 1999; Ozer 2006).

6) Each PI will strive to involve minority and underrepresented students at our respective institutions. This will include participation in field and laboratory work that will expose students to the challenges of inter-disciplinary research and help them develop strategies for bridging the gaps that often separate traditional scientific disciplines. We anticipate at least 3 Ph.D and 2 MA degrees to result.

MANAGEMENT PLAN

This project requires PIs, senior scientists, foreign collaborators, and students to be well organized into five interrelated areas: administration, modeling, data acquisition, data management, and education.

Administration: Dr. Douglas **Kennett** (UO) will assume the role of project director (PD). He will foster communication and synergy between different members of the research team through weekly e-mail, periodic phone/video conferencing, and interaction at annual national professional meetings. He will also attend the HSD PI meeting each year. Students under his supervision will create and maintain the project website for educators and the public, and password protected access to sensitive datasets electronically archived in the Knight Library (UO; see data management below). PIs will be responsible for coordinating their respective field campaigns, but Kennett will assist integrating these efforts with the help of Dr. Keith **Prufer** (UNM) who has an established research station in southern Belize and has strong connections with the local archaeological establishment. Kennett and Prufer will also work with Dr. Jaime Awe to fulfill annual requirements for fieldwork permit renewal. Dr. Awe is the director of the Belize Institute of Archaeology and has over 30 years of professional archaeological experience in Belize. He will assist Prufer and Kennett in developing and implementing the archaeological research design and assist with logistical negotiation with local and national governmental organizations. Kennett will work with the PIs to write annual and final project reports for NSF and the Belizean government.

Modeling: Dr. Bruce **Winterhalder** (UCD) is charged with coordinating our integrated modeling efforts and will work closely with the project climate modeler Dr. Patrick **Bartlein** (UO). Winterhalder and his team will develop multivariate models to explore climate, environment and intensification in the development and persistence of complex sociopolitical systems. He will work closely with **Kennett**, **Prufer** and **Zarger** to determine the economic, social, political, and ideological parameters necessary to operationalize the IFD/IDD model and associated statistical analyses. He will work closely with the UCD, Depart. of Anthropology, biomathematician, Dr. Mark Grote. Dr. Kevin **Cannariato** (USC) will synthesize existing regional paleoclimate data in collaboration with Bartlein. Bartlein will establish interrelated landscape transformation models and parameters in consultation with Kennett during the first two years of the project.

Data Acquisition: Fieldwork and data analysis will be conducted by four inter-related research teams. These research teams will be coordinated by Dr. Keith **Prufer** (Archaeology), Dr. Rebecca **Zarger** and Dr. Bruce **Winterhalder** (Ethnography), Dr. Kevin **Cannariato** (Paleoclimate), and Dr. Douglas **Kennett** (Landscape Transformation).

***Paleoclimate**:* Dr. Kevin **Cannariato** will coordinate the collection and analysis of speleothems from Yok Balum cave near Uxbenká in southern Belize and articulate these high-resolution records with other broadscale records of climate change. In June of 2006 Cannariato, **Kennett** and **Prufer** collected 10 speleothems from this cave. He will also coordinate associated long-term environmental monitoring of this cave with help from **Zarger** and collect historical and modern instrumental and archival weather data with the help of **Prufer**. Cannariato will work with Dr. Yemane **Asmerom** (UNM) to determine the age of these speleothems using U/Th measurement. He will oversee incremental sampling to establish high-resolution $\delta^{18}O$ rainfall records.

***Landscape Transformation**:* Dr. Douglas **Kennett** will coordinate and synthesize information about modern and prehistoric biotic systems and landscape transformation. He has established a Geographic Information System (GIS) for southern Belize and will coordinate the acquisition of remote sensed environmental and geographic datasets for the region (e.g., digital elevation models, Landsat 7, Aster, Quickbird, aerial photographs). The GIS and associated relational database will allow for the integration of climatic, environmental, archaeological, archival, and ethnographic datasets on a variety of spatial scales. Kennett will also oversee test excavations at archeological sites and agricultural systems (e.g., terraces, irrigation systems) in conjunction with survey and small-scale testing, coordinated by **Prufer**. Regional geomorphological sequences from river cut exposures and wetland sediments will also be generated. Kennett will work with a postdoctoral researcher to take sediment cores from three wetlands in the vicinity of Uxbenká. This postdoctoral researcher will also produce regional fire records with high-resolution charcoal analysis in consultation with **Bartlein**. Kennett will coordinate pollen analysis with Dr. John **Jones** (WSU).

Archaeology: Dr. Keith **Prufer** will coordinate archaeological fieldwork surrounding Uxbenká. He will work with **Kennett** to use high-resolution Quickbird satellite imagery (sub-meter resolution) to design a stratified random scheme in a 100 km^2 area surrounding Uxbenka. Prufer and Kennett will oversee two archaeological survey teams composed of students and local community members. Different environmental zones will be surveyed for ancient settlements, houses, and agricultural features that were once associated with each of these centers. Surface characteristics and artifacts will guide excavation. This work will refine the settlement history, changes in subsistence economies, changing densities of settlement, and the scale of economic, social and political integration through time.

***Ethnography**:* Dr. Rebecca **Zarger and** Dr. Bruce **Winterhalder** will coordinate the ethnographic work. They will work with Maya community leaders and identify individuals with knowledge about complex ecosystemic relationships. Zarger and her students will conduct interviews to document agro-ecological knowledge and practice, with an emphasis on adaptation to rapid and long-term change. Zarger will also work with Dr. Bruce **Winterhalder** to design and implement observational and experimental research to gauge the climatic, environmental, and anthropogenic variables that contribute to changes in agricultural productivity through time.

Data Management: Dr. Douglas **Kennett** (UO) will work with each PI to prepare databases and associated metadata to be electronically archived in the Knight Library at the UO. These data will also be integrated in a regional database using Geographic Information System (GIS) software, for testing hypotheses generated by our modeling efforts. Digital datasets to be archived will include GIS coverages, relational database, scanned field notes, digitally taped interviews, photographs, video, and all other information. This is part of a larger initiative at the UO to archive digital datasets. Datasets will be connected to the project webpage with password-protected links available to all project personnel. Kennett will be responsible for archiving all media coverage related to the project.

Education: Dr. Rebecca **Zarger** (USF) will coordinate our education plan in close consultation with **Kennett and Prufer.** Zarger will establish a curriculum workbook and associated resources (CD-ROM) for primary and secondary schools in the US and Belize, after revisions based on the two pilot school projects in San Miguel and Santa Cruz. This will be coupled with teacher training workshops in select locations in the US and Belize. Zarger will also work closely with Kennett, Prufer, and the Mopan Maya community of Santa Cruz to establish appropriate educational materials (e.g, exhibits and educational Maya gardens, see Education section) from the project at the site of Uxbenká. The PIs of the inter-related components of this project will be responsible for integrating undergraduates and graduate students into our research and educational objectives.

EXPECTED PROJECT SIGNIFICANCE

Intellectual Merit: Our primary objectives are to: (1) develop an integrated multivariate human-landscape-climate model for the emergence and resilience of complex socioeconomic and political systems and (2) apply and test the predictions of the model with extant data and strategic interdisciplinary research in the tropical Maya lowlands of southern Belize. Climatic variability on multiple timescales can elicit a range of human responses depending on a population's distribution and density, economic modes of production (e.g., small-scale horticulture vs. intensive agriculture), population-dependent anthropogenic environmental effects (e.g., deforestation, erosion), and degree of individual integration into higher order political entities (e.g., states) capable of coercion or ideological manipulation. Models and simulation are essential for exploring the stability and vulnerability of these higher order political systems and their susceptibility to disintegration under dynamically changing environmental, social, and political conditions. Drawing from theory in population and behavioral ecology, we formulate models that integrate key variables thought to affect the origins and persistence of intensified production and political systems. We argue that the model can be generalized with respect to environment and economy, including technologically dependent states. We calibrate and test this model with extant archaeological and ethnographic data from the tropical Maya lowlands of Mesoamerica and strategic empirical work in southern Belize, a well-bounded and documented environmental and cultural context that is ideal for inter-disciplinary empirical study.

Broader Impacts: We anticipate that our integrated modeling efforts and empirical observations will be relevant well beyond the bounds of ancient Maya political systems. With the world's population exceeding six billion, abrupt climate change and human-induced environmental degradation are acute problems. Agricultural expansion, deforestation, soil depletion, and decreasing crop yields contribute to food scarcity and world hunger (Brown 1996). The local effects of food scarcity, social fragmentation, migration, conflict, and political instability, have far reaching consequences. The inter-disciplinary modeling effort that we propose provides a historical perspective on the effects of human colonization, demographic expansion, resource intensification, and climatically-driven environmental change along with inter-related behavioral responses promoting sociopolitical integration or fragmentation. We need, but at present we simply do not have, empirically grounded, dynamic models at regional and millennial scales that link climate and terrestrial environment to socio-political persistence via the adaptive behavior of households situated in real landscapes. Our research will most immediately affect the indigenous Maya communities of southern Belize, currently struggling with the environmental impacts of expanding populations and changes in climate. At a more general level, studying the complexities of human decision-making under changing demographic and environmental conditions and the cascading effects of these decisions on socio-political systems provides a historical perspective of great value to policy makers today (van der Leeuw and Redman 2002).

Our research team is also committed to education on multiple levels, especially the need to reach across boundaries that often impede problem-oriented inter-disciplinary research (Alvarez 1990). We aim to bridge isolated academic traditions and jargon-laden technical language with a new style of integrated scientific research. Our approach parallels recent attention to project-based learning in secondary education that crosscuts traditional subject matters by producing hands-on instruction modules. These teaching modules will also be translated into Spanish. We are already actively engaged in a reciprocal educational relationship in the Mopan Maya community of Santa Cruz. Undergraduate and graduate students involved in this project will acquire inter-disciplinary skills and we anticipate a minimum of 3 Ph.D. and 2 MA degrees resulting from this work. An educational website featuring project resources and results will serve scholars, educators and the general public.

SCHEDULE OF WORK

Year 1 (Sept. 15, 2008-Sept. 14, 2009): The first year will be used to establish the climatic, environmental, and human behavioral parameters of human-landscape-climate interactions in southern Belize. The GIS database necessary for implementing the landscape modeling component will be augmented with regional satellite imagery (LANDSAT 7, ASTER) aerial photographs and paper maps of key environmental or historical datasets (soils, land use, etc.). We will acquire two high-resolution (sub-meter) QUICKBIRD satellite images (100 km^2) surrounding Uxbenká. $\delta^{18}O$ analysis of U/Th-dated speleothems from Yok Bolum cave will begin. Archaeological and paleoenvironmental field studies will be conducted between April and June. Ethnographic research will start in the Mopan Maya community of Santa Cruz and educational outreach will be initiated with local teachers. Experimental agricultural plots will be established with community members willing to participate and sites selected for interpretive gardens at Uxbenká. Additional speleothems will be collected from Yok Bolum cave. All meteorological and environmental monitoring stations will be established. U/Th-dating of speleothems and AMS radiocarbon dating of archaeological sequences will be conducted between June and September. Preliminary results will be presented at the annual Belize archaeology conference and at the HSD PI meeting in this and in subsequent years. Presentation at the Belize archeology meeting is a requirement of the permitting process. The project website will be available early in the year to disseminate information.

Year 2 (Sept. 15, 2009-Sept. 14, 2010): High-resolution paleoclimatic study will continue. Sediment cores will be taken from wetland environments in the vicinity of Uxbenká. Detailed charcoal and pollen analysis from wetland sediments will be conducted. AMS radiocarbon dates will be used to define the chronology of paleoenvironmental sequences between 4000 and 1500 years BP. Chronological work on select speleothems (U/Th) will be completed and high-resolution $\delta^{18}O$ work will continue. Archaeological fieldwork (April to June) will concentrate on survey and intensive sampling of prehistoric settlements and agricultural features surrounding Uxbenká. Ethnographic and experimental agricultural work will continue in Santa Cruz, expanding along with educational outreach to San Miguel, a Q'eqchi' Maya community to the northeast. Interpretive gardens at Uxbenká will be established and maintained. A two-day curriculum design workshop, co-chaired by the Belizean and Tampa curriculum coordinators, will be held for San Miguel and Santa Cruz teachers and education stakeholders at regional or national Ministry of Education offices. Archaeological, ethnographic, and paleoenvironmental data will be integrated into a GIS spatial database and used to refine integrated human-landscape-climate model. Preliminary results will be presented at national meetings during this and subsequent years.

Year 3 (Sept. 15, 2010-Sept. 14, 2011): Inter-disciplinary data will be synthesized and used to test model hypotheses and predictions generated in Year 1. We anticipate archaeological fieldwork to be completed in this year. High-resolution $\delta^{18}O$ speleothem work will be completed; ethnographic and experimental agricultural work will continue. Archaeological fieldwork and analysis in Belize will be completed and materials will be curated with the Belize Institute of Archaeology. Ethnographic and experimental agricultural work will conclude and a plan put in place to maintain the interpretive gardens through the Uxbenká cultural center. The education curricula will be finalized, printed, and distributed to primary and secondary schools in Belize and Tampa. The integrated (climate, landscape, agro-ecology and political economy) model will be developed to operational form. PIs and senior researchers will finalize datasets and archive them digitally in the Knight Library (UO). Joint publications will be prepared. Artifact illustrations, maps, soil profiles, architectural drawings, and other graphics will be produced for final reporting and publication. Teacher training workshops will be given in select locations in the US and Belize, including our host Maya communities. We will also convene an inter-disciplinary session at AAAS to disseminate results.

RESULTS FROM PRIOR NSF SUPPORT (PIs/Co-PIs; In Alphabetical Order)

Asmeron: ATM-0214333 ($181,573) 07/02-07/05: Holocene paleoclimate for southwestern USA from annual banding in stalagmites. The goal was to obtain a high-resolution climate record for the Holocene of the southwestern United States from annually banded speleothems. We have published eight papers from this effort, including one in *Science* and three in *Geology.*

Bartlein: ATM-9910638 ($286,536) 09/99-08/03: Testing Earth-System Models with Paleoenvironmental Observations. This collaborative project (Univ. Oregon, Wisconsin, Brown. and the Max-Plank Institute for Biogeochemistry) included development of the models, data sets, and diagnostic approaches appropriate for using the paleoclimatic record to test Earth-system models. Work at Oregon included data-model comparisons, applications of nested-model approaches for paleoclimate simulations, data set and methods development, diagnosis of the causes of mid-Holocene climate anomalies, analysis of continental-scale vegetation dynamics, projection of vegetation responses to future climate changes, and development of guidelines for the effective use of color in visualizing and analyzing geoscience data. More than 20 publications resulted from this support.

Cannariato: ATM-0502615 ($448,589) 07/05-06/07: w/ Lowell D. Stott (PI); To test the hypothesis that recurring century-length episodes of reduced summer monsoon precipitation are linked to ocean atmosphere dynamics in the tropical pacific using marine and stalagmite paleoclimate records. Work thus far has resulted in 4 papers including one in Geophysical Research Letters entitled " A 900-year (600 to 1500 A.D.) record of the Indian summer monsoon precipitation from the core monsoon zone of India." **OCE-0317621 ($600,000)** 7/03-6/05: w/ Lowell D. Stott (PI); To generate high-resolution Holocene marine and stalagmite paleoclimate records from Asia and the Indo-Pacific to test the temporal and spatial pattern of millennial scale climate variability of atmospheric convection and the position of the ITCZ. Results were presented in 4 papers, including one in Nature entitled "Decline of surface temperature and salinity in the western tropical Pacific Ocean in the Holocene epoch".

Kennett: BCS-0211214 ($186,353) 09/02-09/05 continued from **SBE-0089849 ($64,557)** 01/01-02/02: This was an inter-disciplinary project designed to study the transition to agriculture along the Pacific Coast of Mexico. It has resulted in 6 comprehensive reports, 6 peer-reviewed papers and 1 book entitled *Behavioral Ecology and the Transition to Agriculture* (2006; UC Press, with B. Winterhalder). **SBR-9521974 ($12,000)** 07/95-07/96*:* To study the environmental, demographic, and social contexts for cultural stability and change on the Channel Islands of California during the Holocene. The results of this work were presented in 30 peer-reviewed papers, a Ph.D. thesis (1998), and book entitled *The Island Chumash: Behavioral Ecology of a Maritime Society* (2005; UC Press).

Prufer: BCS-9901265 ($11,649) 02/99-11/00: The role of social hierarchies, elite ritual practice, and community-wide planning as reflected in the use of caves and rockshelters. Results have been presented in 17 peer reviewed articles and book chapters, 1 PhD thesis, and formed the basis for two edited volumes (U Texas Press, and U Press of Colorado, with J. Brady). **BCS-0620445 ($123,830)** 08/06-07/09: To investigate the rise of regional political complexity and prestige-based elite interactions through investigations at Uxbenká, Belize. This is a new project that complements the proposed work; publications are forthcoming.

Winterhalder: BNS-8313190 ($117,000) 7/84-6/87 "Production, Storage, and Exchange (PSE) in a Terraced Environment on the Eastern Andean Escarpment." Multi-year, ecological anthropology research on factors mitigating production risk at household level in a peasant community practicing dry land agricultural and pastoralism at high altitude. The project resulted in five PhDs, 4 research monographs and ten journal publications. Newly available statistical techniques (multi-level, random and fixed effects models for categorical data) have prompted preparation of a fifth monograph on time allocation (*in prep*).