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COMPUTATIONAL MODELING AND NEOLITHIC SOCIOECOLOGICAL DYNAMICS: A CASE STUDY FROM SOUTHWEST ASIA

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Archaeology has an opportunity to offer major contributions to our understanding of the long-term interactions of humans and the environment. To do so, we must elucidate dynamic socioecological processes that generally operate at regional scales. However, the archaeological record is sparse, discontinuous, and static. Recent advances in computational modeling provide the potential for creating experimental laboratories where dynamic processes can be simulated and their results compared against the archaeological record. Coupling computational modeling with the empirical record in this way can increase the rigor of our explanations while making more transparent the concepts on which they are based. We offer an example of such an experimental laboratory to study the long-term effects of varying landuse practices by subsistence farmers on landscapes, and compare the results with the Levantine Neolithic archaeological record. Different combinations of intensive and shifting cultivation, ovicaprid grazing, and settlement size are modeled for the Wadi Ziqlab drainage of northern Jordan. The results offer insight into conditions under which previously successful (and sustainable) landuse practices can pass an imperceptible threshold and lead to undesirable landscape consequences. This may also help explain long-term social, economic, and settlement changes in the Neolithic of Southwest Asia.

La arqueología tiene la oportunidad de contribuir en gran parte al conocimiento de las interacciones entre la humanidad y el medio ambiente sobre tiempos largos. Para realizarlo, hay que concretar los procesos dinámicos de la socioecologia que tienen lugar a escala regional. Sin embargo, el registro arqueológico es disperso, discontinuo, y estático. Los recientes avances en el modelado de cómputo ofrecen el potencial de construir laboratorios de experimentación donde se puede simular procesos dinámicos y contrastar los resultados comparados con el registro arqueológico. La combinación de la modelización y el registro empírico puede incrementar el rigor de las explicaciones arqueológicas e igualmente hacer mas transparentes las ideas en que se basan. Presentamos aquí un ejemplo de tal laboratorio para el estudio de los efectos a largo plazo del uso de la tierra por campesinos sobre los paisajes, y comparar los resultados con el registro arqueológico del Neolítico Levantino. Combinaciones diferentes de cultivo intensivo y extensivo, del pastoreo de ovicápridos, y de asentamientos de varios tamaños se simulan para la cuenca del Wadi Ziqlab en el Norte de Jordania. Los resultados de tales experimentos proporcionan una nueva perspectiva sobre las condiciones en las que formas originalmente prósperas de agricultura pueden pasar un umbral imperceptible y tener consecuencias indeseables. También pueden contribuir a entender los cambios sociales, económicos, y de pautas de asentamiento en el curso del Neolítico en el Próximo Oriente.

The ability to document the long-term interactions between societies and landscapes has long been a major focus of archaeological research (Barton et al. 2004; Braidwood et al. 1983; Butzer 1982, 1996; Fisher and Thurston 1999; Flannery 1986; Kirch 2005; Redman 1999, 2004). Recently, this has been proposed as a domain in which archaeology can offer guidance on current issues of global change and environmental policy (Fisher and Feinman 2005; van der Leeuw 2000; van der Leeuw and Redman 2002). Indeed, with its command of past human ecology and the social and environmental impacts of landuse decisions, archaeology is positioned to provide scien-

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tists and policy makers with valuable information on the multiscale consequences of individual and social behaviors in diverse contexts. However, the nature of the archaeological record and our means of drawing inferences from it pose significant challenges to any program that seeks to apply knowledge from the past to today's problems.

The interactions between societies and their environments take place at multiple spatial and temporal scales, involving complex relationships and feedbacks. For many questions relevant to ongoing human-environmental concerns, the most significant interactions are those that act on a regional scale of hectares to square kilometers rather than centimeters, or even a few meters; rainfall, sheetwash, stream flow, animal husbandry, land clearance and cultivation, irrigation systems, and terracing are all regional phenomena. But the data archaeologists acquire to study these complexly recursive, regional-scale phenomena most often come from very few, widely scattered, and irregularly dispersed points on the landscape—the careful excavation of a few square meters in a prehistoric settlement, a pollen core in an ancient lakebed, an exposure of sediments and soil in a stream bank. These data are almost always static, highly altered, secondary or tertiary residues of dynamic processes—never the processes themselves. Through careful application of middle-range theory and uniformitarian principles, archaeologists endeavor to verbally re-create (i.e., "reconstruct") the complex dynamics of past sociecological systems through complex chains of inference. With over a century and a half of accumulated experience, archaeologists do a truly amazing job of extracting useful information from usually poor quality and often ambiguous data. But because it is also necessary to fill in the enormous gaps between the actual data points with educated speculation, multiple—sometimes conflicting—reconstructions often can be derived from the same set of sparse data. While archaeological accounts of past human-environmental interactions make for compelling reading and can serve as useful cautionary tales, it is not surprising that others outside the field remain reluctant to base policy decisions on archaeological research.

At the same time that other fields are looking to archaeology for guidance on understanding and predicting the long-term dynamics of human society, advances in cybertechnology offer archaeologists a richer and more diverse toolset to use for this purpose—one with the potential to make the archaeological record a basis for rigorous, quantifiable, and testable models of human systems. Recent developments in computational modeling offer new and exciting opportunities for archaeology to move beyond compelling narratives, and begin to represent social dynamics as explicit, quantitative models that can be tested against the archaeological record. In part, these are representative of a trajectory, beginning over two decades ago, that has explored the applications of computer technology to archaeological questions and laid important groundwork for more widespread use of computational modeling today (e.g., Gaines and Gaines 2000; Kvamme 1999; Westcott and Brandon 2000, along with the collected volumes of the proceedings of the Computer Applications in Archaeology conferences).

We report here on a widely useable computational modeling laboratory for developing and testing hypotheses about the social and natural consequences of changing agropastoral landuse practices. The laboratory is being built as part of the Mediterranean Landscape Dynamics Project, with support from the National Science Foundation. The project's initial focus is on the Mediterranean Basin and socioeconomic systems that span the beginning of farming to the beginning of urban life. An important component of this modeling laboratory is the ability to simulate surface process dynamics (e.g., erosion and deposition) at regional spatial scales and at decadal to centennial temporal scales. In this paper, we describe the components and algorithms of the modeling environment (see Mayer and Sarjoughian 2007; Mayer et al. 2006; Ullah 2010 for additional details), and demonstrate its potential as a laboratory for studying socioecological dynamics in a case study from northern Jordan. We use open source software that is freely available to researchers globally to create a modeling environment that can easily be adapted to other terrestrial landscapes beyond the Mediterranean.

At the outset, we want to be clear about our goals here. We are *not* attempting to reconstruct prehistoric societies and their interactions with ancient environments in a digital setting. As we indicated above, the incomplete and ambiguous nature of the archaeological record makes detailed reconstructions of complex and dynamic human societies difficult or even impossible to verify, and problematic from a scientific standpoint. Our aim, rather, is to model the outcomes of a carefully and explicitly specified suite of human-environmental interactions (i.e., hypotheses about socioecological dynamics) and compare these outcomes with a well-studied archaeological record of long-term socioecological change. Importantly, this approach permits us to carry out experiments to study consequences of alternative landuse practices over long time periods and at regional scales, and to do so in a controlled, laboratory environment. Experimental social science at these temporal and spatial scales is not possible with observational studies of modern subsistence farmers nor is it possible through re-creating past societies from inductive interpretation of the archaeological record, however carefully done. In other words, we are *not* substituting a computer simulation of the human past for narrative prose, but endeavor to illustrate the potential of archaeology as a science of long-term social dynamics.

Building a Landuse-Landscape Modeling Laboratory

The landuse-landscape dynamics (LLD) component of the modeling laboratory is constructed within the Geographic Resource Analysis and Support System (GRASS), an open-source, general purpose geographic information system (GIS) (http://grass.osgeo.org) (Neteler and Mitasova 2008). GRASS can be used on all common desktop computer operating systems, and has a rich set of geospatial analysis and modeling functions especially useful in archaeology and environmental sciences (Barton et al. 2007; Mitasova and Neteler 2004).

Two features of GRASS make it particularly well suited for use as a modeling platform for socioecological dynamics. First, as with other open-source software packages, the underlying programming code is accessible to anyone who wishes to modify or enhance the program. Second, GRASS is highly "scriptable." That is, its more than 300 geospatial analysis, visualization, and data management functions can be combined easily, using common scripting languages, to produce custom applications and automated workflows with integrated GUI interfaces. Our modeling laboratory is mostly constructed in the form of scripts that chain together multiple GRASS functions in new ways. The modeling applications we describe here can be modified by archaeologists with limited programming skills and familiarity with GIS.

Raster GIS for Landscape Modeling

The primary building blocks for the modeling landscapes are topography, soils and/or unconsolidated surface sediments, vegetation (also called land-cover), and regional climate. A landscape and its features can be represented within a GIS environment in two common ways: as a set of vector objects or as a surface of raster cells (Conolly and Lake 2006; Wheatley and Gillings 2002). Vector objects are more familiar to archaeologists making digital or paper maps, and include sites represented as points, rivers represented as arcs or polylines, and agricultural fields represented as areas or polygons. Rasters are less common in archaeological applications but, as discussed below, are more useful for landuse-landscape modeling. When a landscape is represented in raster format, it is divided into many equal-sized cells, and data recorded for each cell—elevation, slope, precipitation received, vegetation, or soil type, for example. When archaeologists employ an excavation strategy in which artifacts, faunal remains, and sediment samples are collected and analyzed at the level of a gridded field provenience unit, they are employing a methodological approach very much like that of raster GIS analysis. For the LLD modeling laboratory, topography is represented as a digital elevation model (DEM) in which each raster cell is coded with its elevation. From a DEM, it is a simple matter in a GIS like GRASS to derive related information such as the slope and aspect (or slope direction) of each cell. Surface sediments/soils and vegetation are similarly represented in raster format by maps in which the cells are coded with erodibility values and land-cover type.

Our focus here is on terrestrial alluvial systems, in which flowing water—described by a set of much-studied, well-understood physical laws—is the primary agent responsible for the entrainment (i.e., erosion), transport, and deposition of surface sediments. This is a function of the amount of water available and its velocity, which in turn are functions of the amount of precipitation, infiltration rate, slope, and topographic features (e.g., channel or hilltop); the erodibility of the surface, which is a function of sediment/soil thickness and composition; and the ability of vegetation (or constructed features like terraces) to slow flowing water and stabilize surface sediment/soil. Although the laws themselves are fairly simple, their real-world operation across variable surfaces is complex. However, they can be simulated in a raster GIS environment, where erosion/transport/deposition values can be calculated for each cell independently based on estimations of the amount of water flowing into and out of the cell, the cell's unique location in the overall topography, the overall characteristics of the surface sediments/soils in the cell, the generalized characteristics of the vegetation within the cell, and similar information about its neighboring cells.

When landscape characteristics are represented as a set of raster maps (e.g., maps for elevation, slope, vegetation, erodibility, etc.) with aligned, equal-sized cells (the norm in a GIS), they can be combined to produce a complex landscape model using a conceptually simple mathematical approach called "map algebra" (also called "image math" for aerial photography and satellite imagery). The resulting model is a new raster map where each cell is a mathematical function of the corresponding cells in the original landscape maps. For example, imagine a set of raster maps where each cell in a *slope* map is coded in degrees above the horizontal (steep slopes have high numbers), cells of a soil *erodibility* map are coded as number that range from 0 (not erodible) to 1 (very erodible), and *vegetation* map cells are coded from 1 (bare ground) to 50 (forest). If we use map algebra to calculate

$$\frac{slope \cdot erodibility}{vegetation},$$

the resulting erosion risk map will have large values (highly susceptible to erosion) in cells where the input maps have steep slopes, erodible soils, and minimal vegetation, and will have small values (not at risk of erosion) in cells where the input maps have low slopes, non-erodible soils, and forest. As described below in more detail, our LLD modeling laboratory can make analogous, though more complex, calculations for an entire landscape to create a map of the estimated depth of erosion or thickness of deposition in any cell in the landscape.

Modeling Dynamics in a GIS Environment

As mentioned above, the GRASS GIS environment supports dynamic modeling particularly well because functions for geospatial data management and analysis, including sophisticated map algebra, can be chained together in scripts. When these functions are combined in recursive loops, where a map produced by a suite of manipulations can be used as input to a subsequent iteration of the same manipulations, such scripts can drive dynamic models that simulate landscape change over time. The model detailed below combines complex GIS functions and map algebra to estimate the net erosion or deposition in each landscape cell. These amounts are subtracted from (for erosion) or added to (for deposition) the elevation of the cell in a DEM to create a new DEM, which represents the predicted new surface topography after one model year. This new DEM is then used as the input topography to a new iteration of the model, simulating cumulative landscape change through time.

We developed the dynamic landuse-landscape models described here in BASH shell scripts—an inelegant, but simple scripting language found on almost all Linux and Unix (including Macintosh OS X) systems and which can be installed in Windows. However, the laboratory could be re-created in any high-level language or scripting environment like open-source Python (we are currently developing a Python version of the model), Perl, Ruby, or even proprietary Microsoft Visual Basic that can be used to chain GRASS functions.

Calculating Surface Erosion and Deposition

In the geomorphological literature, there are various mathematical expressions of the physical laws that govern the flow of water across landscapes and its ability to erode, entrain, transport, and deposit sediments—depending on the processes to be represented, the simplicity of representation desired, and the degree of resolution desired (Clevis et al. 2006; Degani et al. 1979; Mitas and Mitasova 1998; Mitasova, Hofierka, Zlocha, and Iverson 1996; Mitasova and Mitas 2001a, 2001b; Peeters et al. 2006; Singh and Phadke 2006; Warren et al. 2005; Wischmeier et al. 1971; Wischmeier and Smith 1978). We use a sediment transport limited case of erosion and deposition based on concepts described by Kirkby (1971), adapted for two dimensional landscapes by Moore and Burch (1986), and operationalized in a GIS environment by Mitasova (Mitasova, Hofierka, Zlocha, and Iverson 1996). It combines Universal Soil Loss Equation (USLE/RUSLE) parameters and upslope contributing area per unit contour width to estimate sediment flow at sediment transport capacity, and calculate net erosion and deposition across each landscape cell (American Society of Agricultural Engineers 2003; Degani et al. 1979; Mitasova et al. 2001; Mitasova, Mitas, Brown, and Johnston 1996; Mitasova et al. 2004; Singh and Phadke 2006; Warren et al. 2005; Wischmeier 1976; Wischmeier et al. 1971; Wischmeier and Smith 1978). Moore and Burch referred to this approach as Unit Stream Power Erosion/Deposition (USPED). This name is somewhat misleading, however, as the algorithm focuses on hillslopes, small watersheds, and small channels (i.e., rills and gullies) rather than stream power, and is less applicable to larger streams and rivers (Warren et al. 2005). Hence, we refer to it here more simply as *hillslope erosion/deposition* or *HED*. It is useful for many archaeological settings including arid, semiarid, and xeric regions like those that surround much of the Mediterranean basin.

Net erosion and deposition rates are computed from the change in sediment flow across cells of a DEM. We approximate sediment flow rate from sediment transport capacity, assuming that water flowing over landscapes normally carries sediment at capacity. Transport capacity is calculated by combining a rainfall coefficient (R), soil erodibility coefficient (K), and coefficient for the ability of vegetation to prevent erosion (C) from RUSLE with an estimate of topographically driven stream power as shown in equation (1) (See Table 1 for a description of the coefficients).

$$T = R\,K\,C\,A^{m}\,(sin\;\beta)^{n} \qquad (1)$$

Sediment flow rate (T) is controlled largely by the amount of water flowing (contributing area, A^m), its velocity (a function of slope, $[sin\;\beta]^n$), the erodibility of the substrate (K), and the ability of the vegetation cover to prevent erosion (C).

Net erosion and deposition rates are computed as change in sediment flow in the x and y directions across a cell, as shown in equation (2)

$$HED = \frac{\delta(T\cdot\cos(\alpha))}{\delta x} + \frac{\delta(T\cdot\sin(\alpha))}{\delta y}, \qquad (2)$$

where HED is net erosion or deposition rate for sediment and (is the topographic aspect (i.e., direction of flow) for a cell. Whether flowing water will erode or deposit sediment in a particular cell is determined by the *change* in sediment flow (transport capacity) from one cell to the next. If the transport capacity increases (for example, due to an increase in the steepness of the slope or amount of flowing water), more sediment will be entrained and erosion will occur; if the transport capacity decreases (for example, due to a decrease in slope or water flow) sediment will be deposited.

HED normally is calculated as units of weight per unit area each year (tons/ha.yr). In order to iteratively model erosion and deposition across a landscape over time, however, HED can be re-expressed as depth of sediment per cell. This is done by multiplying it by the unit density of the soil and the hectares per cell, and dividing by the number of volumetric units (e.g., meters for volume in m^3) per cell. Soil density was approximated using the method outlined by Rawls (1983) combining the percentages of sand, silt, clay and organic matter—and estimated for *Terra Rossa* soils on the basis of empirical studies by Onori et al (2006).

Implementing the HED algorithm in a GRASS script combines GIS modules for calculating slope, aspect, and flow accumulation (the amount of water that flows across each cell) using map algebra. Data used by the script includes a map of initial surface topography (a raster DEM), soil erodibility (a constant for uniform soil or a raster map for variable soil), vegetation cover (a constant or raster map), and rainfall intensity (a constant only). We also create an underlying bedrock topography map (a raster DEM) that provides a limit to the total depth of unconsolidated sediment that can be eroded. Soil erodibility, vegetation cover, and rainfall are expressed as the K-factor, C-factor, and R-factor for the RUSLE, and have been calculated empirically for a variety of settings (Boellstorff and Benito 2005; Essa 2004; Hammad et al. 2004; Martínez-Casasnovas, 2000 #4092; Renard et al. 1997; Renard and Freimund 1994). Running the

Table 1. Coefficients Used in the Erosion/Deposition (HED) Modeling Algorithm.

Coefficient	Meaning	Units
R	Rainfall intensity factor	(MJ.mm)/(ha.hr.year)
K	Soil erodability	(tons.ha.hr)/(ha.MJ.mm)
C	Vegetation resistance to erosion	unitless weighting factor
A	Upslope contributing area per unit width	$m^2/m = m$
β	Slope of a cell[1]	degrees
m & *n*	Empirically derived weighting factors that vary with type of flow (soil creep, overland flow, rills and gullies, landslides)	unitless weighting factor
HED	Net erosion/deposition rate	tons/ha.year

script creates a new map where each raster cell carries a numerical value of net HED calculated for that cell under the specified conditions of rainfall intensity, soil erodibility, water flow, and vegetation cover. This map of net HED is then re-expressed as sediment depth and added to (for deposition) or subtracted from (for erosion) the topography map from the previous time step, to create a new DEM after a cycle of landuse and landscape change.

Experiments in Landuse-Landscape Dynamics

The LLD simulation laboratory allows us to conduct experiments on the long-term effects of landuse practices on Mediterranean landscapes. We present some of the initial experimental results here to exemplify the potential of this approach for studying the dynamics of human socioecological systems. As noted above, our primary intent is not to present a new way to reconstruct Neolithic agropastoral practices. However, in order to use the archaeological record to test the long-term outcomes of landuse-landscape modeling, it is important to situate the modeling experiments within a real landscape for which we have good archaeological and paleoenvironmental data. In this way, we can compare the simulation results with settlement and landscape data from the prehistoric record, in order to refine the laboratory's ability to model real-world interactions between humans and landscapes.

Archaeological Context for LLD Experiments

The case study presented here is set in the watershed of the Wadi Ziqlab in northwestern Jordan. The Ziqlab is a tributary of the Jordan River, draining an area of about 234 sq. km (Figure 1). It has been studied archaeologically since 1981 by Banning and colleagues (Banning 1996), who identified at least 6 major Neolithic settlements in the Ziqlab and adjacent wadis. These range in size from the tiny hamlet of Tabaqat al-Bûma (< ca. 2000 m^2) to the village of Tell Rakkan (< ca. 100,000 m^2). Tell Rakkan is dated to the Prepottery Neolithic B (PPNB: 9500–7500 cal-BP) on the basis of artifacts while Tabaqat al-Bûma is dated to the Late Neolithic (LN, also called the Pottery Neolithic: 8000/7500–6000 cal-B.P.) (Simmons 2007). Radiocarbon dates from Tabaqat al-Bûma give it an estimated age of 7706–7000 cal-B.P. (Banning 2007). Several of the Ziqlab sites have been at partially excavated, offering data useful for estimating the number of inhabitants at each settlement.

The Wadi Ziqlab sites, and the Neolithic in general, preserve a record of the long-term socioecology of subsistence farming. Based on information from these and other Levantine Neolithic sites—e.g., Abu Hureyra, Mureybat, `Ain Ghazal, Wadi Shu'eib, Jericho, Aswad, Basta (Banning 1998; Kuijt and Goring-Morris 2002; Twiss 2007])—the Neolithic inhabitants of the Wadi Ziqlab likely cultivated cereals (Emmer wheat and barley) and pulses (lentils and chickpeas), herded sheep and goats, and raised domestic pigs (Banning 1995). However, we do not know to what extent cultivation emphasized intensive horticulture—located close to settlements, employing short fallow cycles, and relying on manure from domestic animals and crop rotation to maintain soil fertility—or more extensive shifting cultivation in the Mediterranean woodland—extending a greater distance from settlement and relying on long fallow cycles to maintain soil productivity. Similarly, we do not know whether domestic animals generally were closely

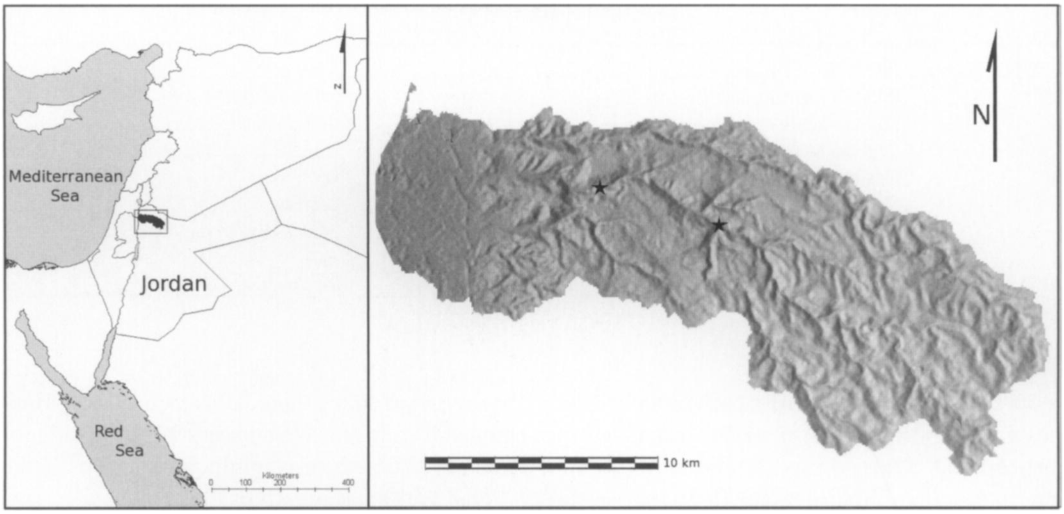

Figure 1. Location of the study area and Wadi Ziqlab watershed in northern Jordan.

managed and kept near settlements, or were allowed to graze more widely in the surrounding woodlands. With the LLD modeling laboratory, however, we can experimentally model various forms of agropastoral landuse, and compare the results with the Ziqlab Neolithic record.

Agropastoral Catchments and Landuse

In the modeling example discussed here, we used a digital topographic base map (i.e., DEM) derived from a 30x30m Terra ASTER (satellite imagery) DEM and resampled to 15x15m with regularized spline tension interpolation (Mitasova and Mitas 1993). For experimental modeling of alternative agricultural practices, we selected two known archaeological sites in the Wadi Ziqlab—Tell Rakkan and Tabaqat al-Bûma, mentioned above—to represent the range of social and environmental contexts of subsistence agriculture and grazing in this region. Building on the approach pioneered by Hill (1998) and ethnoarchaeological studies of small-scale horticulture in Southwestern Asia (Allan et al. 1972; Falconer et al. 1994; Kamp 1987; Kramer 1980; Kramer 1982; Watson 1979), we calculated the total hectares of intensive cereal cultivation (i.e., without a fallow cycle) needed to support the number of inhabitants estimated to have lived at each site. Tabaqat al-Bûma was a small hamlet of 1-5 families, while Tell Rakkan was a small village of perhaps 5–20 families (Banning 1998, 2003). For shifting cultivation, we assumed a five-year fallow cycle and multiplied the hectares needed for cultivation around each settlement by five, since only 20 percent would be in cultivation at any one time. Using GIS tools, we then identified the number of landscape cells around each site equal to the total area needed for agriculture (for both intensive and shifting cultivation) that also were sufficiently level for simple farming (≤ 10° [see Bevan and Conolly 2002]) and which required a minimum effort to reach on foot (a function of distance and slope). This represents the land most likely to be directly impacted by cultivation.

We calculated the grazing catchment around each site in a similar way. We used ethnohistoric data to estimate the number of ovicaprids needed to support the inhabitants of each site and the total hectares of Mediterranean woodland needed to support these animals (Blench 1998; Khazanov 1994). We assumed that no more than a third of the catchment would have been actively grazed during any one year, and so multiplied it by a factor of three. We again used GIS tools to identify the total number of landscape cells equal to the amount grazing land needed, while minimizing walking effort to reach the landscape cells. We did not limit grazing to areas of low slope, since grazing regularly takes place on steep slopes as well as level land. These initial parameters could be varied in future simulations, of course, an important aspect of this exper-

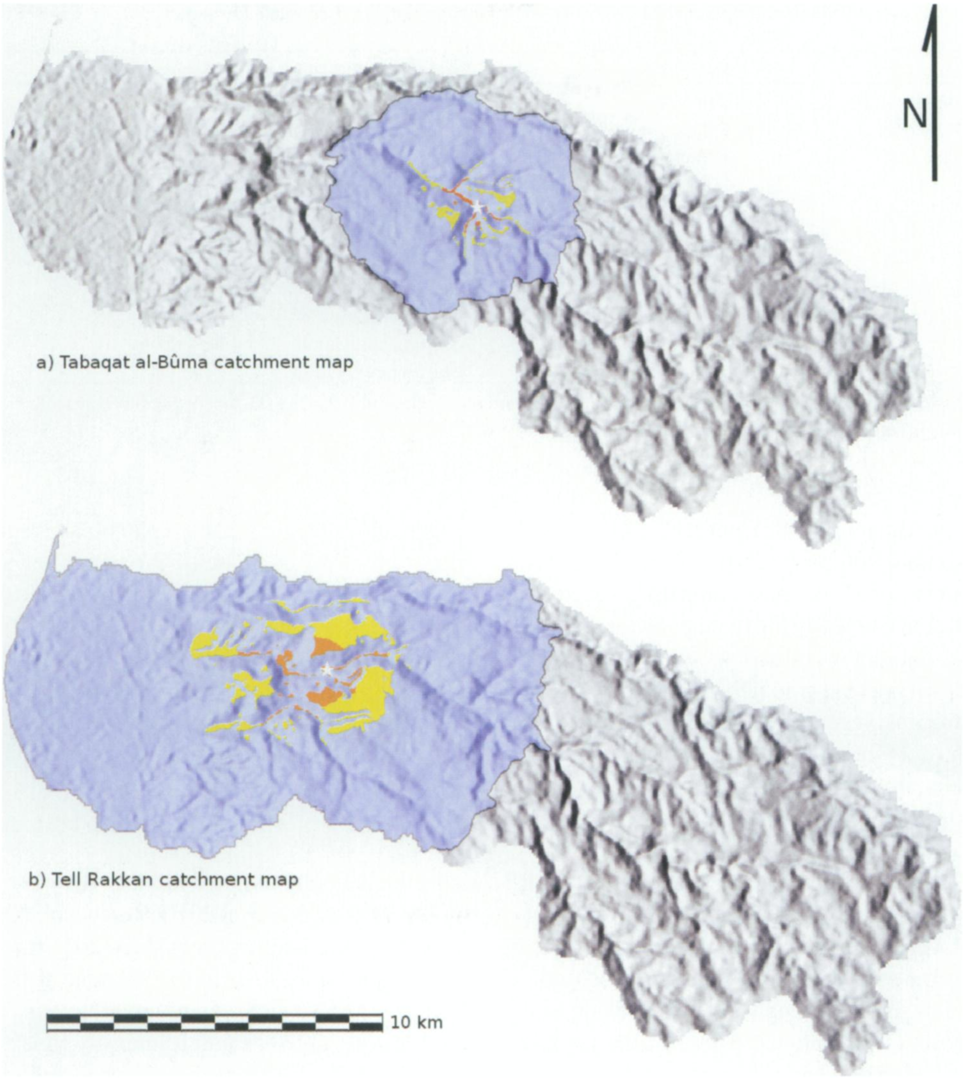

Figure 2. Catchments for intensive cultivation, shifting cultivation, and grazing around Tell Rakkan and Tabaqat al-Bûma. Grazing catchments in blue, intensive cultivation catchments in orange, shifting cultivation catchments include yellow and orange shaded areas. Stars show settlement locations.

imental approach. The catchments for intensive and shifting cultivation, and grazing around Tell Rakkan and Tabaqat al-Bûma are shown in Figure 2.

We used a stochastic algorithm to simulate human landuse over time. All land in an intensive cultivation catchment was treated as being farmed each year. For shifting cultivation, we randomly selected 20 percent of the shifting cultivation catchment to be farmed each year. Likewise, to simulate grazing, we randomly selected 33 percent of the grazing catchment and non-cultivated cells of the cultivation catchment (i.e., fallowed land when modeling shifting cultivation) to be used each year.

Simulating Land-cover Change

Neolithic-level simple farming affects landscape dynamics primarily by changing vegetation cover (Rollefson and Kohler-Rollefson 1992; Schmidtchen and Bork 2003). Based on prior paleoenvironmental studies, we assumed that the region of northern Jordan modeled here was largely covered in Mediterranean woodland in the early

Table 2. Experimental Protocols for Simulating Landuse/Landscale Dynamics.

Settlement	Precipitation & Soil	Agropastoral Landuse Experiments	
Small village	918.5 mm/yr	No cultivation	No grazing
(like Tell Rakkan	R-factor = 6.69	Intensive cultivation	No grazing
ca. 8400 cal B.P.)	K-factor = .42	Intensive cultivation	Grazing
		Shifting cultivation	No grazing
		Shifting cultivation	Grazing
Hamlet	783.7 mm/yr	No cultivation	No grazing
(like Tabaqat al-Bûma	R-factor = 5.26	Intensive cultivation	No grazing
ca. 7400 cal B.P.)	K-factor = .42	Intensive cultivation	Grazing
		Shifting cultivation	No grazing
		Shifting cultivation	Grazing

R-factor is derived from annual precipitation following Renard and Freimund (1994); K-factor for Mediterranean Terra Rossa soils is based on work by di Piazza, di Stefano, and Ferro (2007).

Holocene (Banning 1995; Hunt et al. 2004; Kohler-Rollefson and Rollefson 1990). Cultivation requires the removal of all or most competing vegetation from an active field (by fire or other method). Grazing does not remove all vegetation in a single season, but will instead gradually reduce the ability of the remaining vegetation to protect the land from erosion. If a plot is repeatedly grazed, however, it can eventually be cleared of most or all vegetation (Katakura 1977; Khresat et al. 1998; Stuth and Kamau 1989).

In landscape cells that previously were modified by grazing or cultivation, but subsequently unused, vegetation will begin to regrow. Although vegetation succession can be complicated—affected by the remaining soil depth and nutrients, the amount of vegetation remaining after landuse, climate, and other edaphic factors such as slope and aspect—we modeled revegetation of cultivated or grazed cells in a simple but realistic way. When left alone, a plot of cleared land regains sufficient woody vegetation cover in 50 years so as to be equivalent to the original, non-anthropogenic, Mediterranean woodland in its ability to resist erosion (i.e., its C-factor value for RUSLE). Succession rates are not well calibrated across the Mediterranean region, but this agrees with empirical data from abandoned fields in Alicante, Spain (Bonet and Pausas 2004, 2007).

Land clearance for cultivation reduces vegetation cover to the equivalent of sparse grassland in terms of its resistance to erosion in our model. Grazing is modeled to reduce vegetation by 4 percent for each year a piece of land is grazed. When neither cultivated nor grazed, a plot of land regains vegetation cover at a rate of 2 percent per year. Hence, a raster cell could start out as woodland (100 percent of its potential resistance to erosion), be cleared for cultivation (dropping to 10 percent), lie fallow for 4 years (rising to 18 percent), be grazed for a year (dropping to 14 percent), and lie fallow for another 10 years (returning to 34 percent of its original resistance to erosion).

Modeling Climate and Soil

Using archaeoclimatology models (Bryson and Bryson 1999; Miller et al 2010; Ruter et al. 2004), we estimated precipitation at 8400 B.P. for Tell Rakkan and at 7400 B.P. for Tabaqat al-Bûma (Table 2). Annual and monthly rainfall was combined into an annual rainfall intensity index (R-factor for RUSLE) for each catchment following the method of Renard and Friemund (1994). We plan future experiments to compare the results of annual vs. sub-annual precipitation modeling.

For the experiments reported here, we used a constant soil erodibility index (K-factor for RUSLE) of .42, derived from a recent study of Mediterranean *Terra Rossa* soils (di Piazza et al. 2007). Spatial variation in soil properties can affect HED. But modern soils have been transformed by millennia of human activities and a considerable (but largely unknown) amount of modern variation in soils is anthropogenic in origin, at least in part, and we cannot rely on modern soil maps to indicate prehistoric conditions. At the same time, our interest in this initial set of experiments is to examine the consequences of different landuse practices.

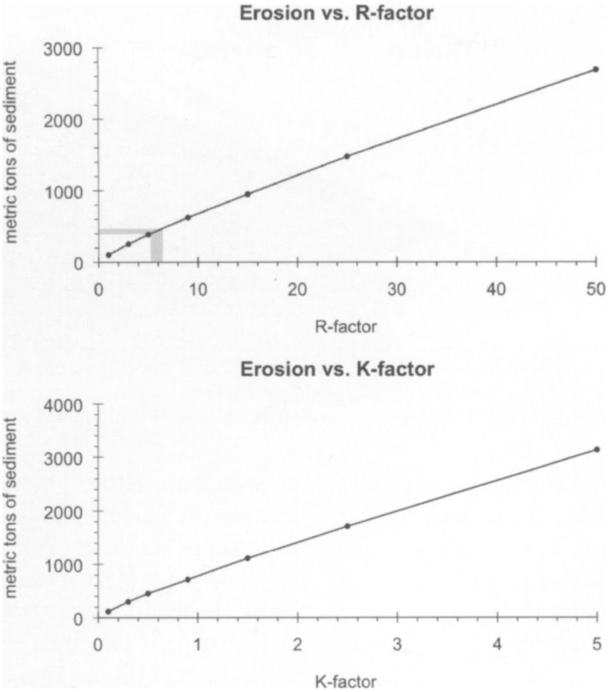

Figure 3. Results of sensitivity analysis of rainfall index (R-factor) and soil erosion index (K-factor). Values show cumulative total erosion for the watershed over a ten year simulation with all other parameters held constant. Deposition (not shown) mirrors erosion for these simulations. Shaded area on R-factor graph shows range of R-factor values used for the hamlet and village simulations.

Virtually all of the Wadi Ziqlab watershed has the same, underlying limestone bedrock and was covered in Mediterranean woodland vegetation. This suggests that modeling the watershed with a constant *Terra Rossa* soil may be more accurate than trying to extrapolate soil parameters from modern maps. If anything, using this constant for soils overestimates the erosion resistance of those small, but agriculturally important, soils on Holocene alluvial sediments that bordered the Wadi channel. Hence, we may be underestimating the magnitude anthropogenic impacts on soils in the bottom of the Wadi, but are reasonably close elsewhere.

Of course, we cannot know the actual climate and soil of the Neolithic in northern Jordan, and we make a number of simplifying assumptions (e.g., constant rainfall and soil characteristics across a modeled catchment) to carry controlled experiments. However, these values are reasonable estimates for this region. In order to compare our experimental results against the empirical data of the archaeological record, it is useful to incorporate such realistic parameters when they are available. Nevertheless, we varied R and K across a range of realistic values for northern Jordan to assess the sensitivity of the model to variance in these parameters. We carried out these sensitivity tests with shifting cultivation and grazing around a small village like Tell Rakkan because, as discussed below, this setting experiences the greatest fluctuations in erosion and deposition. Figure 3 shows the sensitivity of erosion to variations in R and K. In both cases, erosion increases linearly with R and K. While erosion can vary considerably over wide values ranges for R and K, it varies little within the range of values typical for eastern Mediterranean climates and soil used here.

Experimental Protocols

Table 2 shows the series of experiments we describe here, varying agropastoral landuse practices and population size. The ten total experiments include two *control* experiments, in which we run the LLD model without human alteration of the landscape. Because the earth's surface is dynamic without human activity, we need to compare landscape

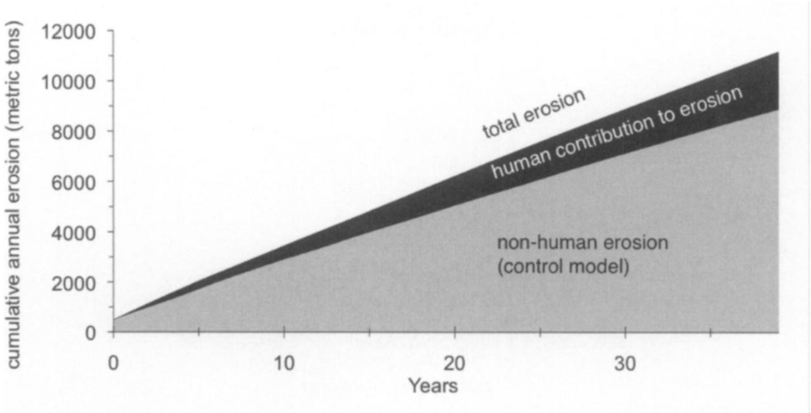

Figure 4. Comparison of anthropogenic and natural erosion for shifting cultivation and grazing at Tell Rakkan.

change modeled with and without human activities to assess anthropogenic effects. Such comparisons can be done using the kind of computational modeling described here, but cannot be inferred from the archaeological and paleoecological records alone because humans *did* live in Wadi Ziqlab, and affected the Ziqlab watershed during the Neolithic.

Each experiment simulated 40 model years of landuse and landscape interactions, approximating the span of two generations. Because model output can vary stochastically each time a simulation is run (even with the same initializing parameters), each experiment was repeated ten times to assess the sensitivity of the model to such stochasticity. The statistics reported here represent the means and variance of the ten repeated runs for each experiment. We also conducted one long experiment to simulate 200 years (approximating 10 generations) of landuse/landscape dynamics to compare with the 40-year results. As with the R and K sensitivity tests, we used a setting of shifting cultivation and grazing around a small village for this long-term experiment.

Each experiment produced a great deal of information; we focus here on anthropogenic impacts to landscapes (HED) and vegetation. These results were recorded across time and space for each experiment as a series of maps, from which we calculated statistics to characterize the impacts of human landuse practices. Because human activity can have an "environmental footprint" (van Vuuren and Bouwman 2005) that extends beyond the area of human landuse, we measured HED and vegetation change for the entire watershed. We calculated *anthropogenic* HED by using map algebra to subtract control model maps from those generated by the experiments incorporating human landuse (Figures 4 and 5). A mean for each model year was calculated for the HED maps from the 10 repeated runs of each experiment. Total erosion and deposition values shown in Figures 6 and 7 are computed from the means of the repeated 10 runs for each model year.

We assessed human impacts on vegetation in a different manner. We calculated the total area of each vegetation class (i.e., from 1 to 50) from the mean of the vegetation maps generated from the 10 repeated runs for each yearly cycle of each experiment. However, it is difficult to display the land areas occupied by 50 vegetation classes across 40 years. Hence, we calculated the coefficient of variation (CV) for the area occupied by each class of vegetation over the 40-year time span for each experiment. High CV values indicate that a vegetation class changed significantly in extent over the time-span modeled, while low values indicate stability of the vegetation class. In Figure 8, we graph CV values for all vegetation classes to compare the impacts of varying landuse practices and population size.

Results

Surface Dynamics

Figures 5–10 display results from the modeling experiments; we review some of the most notable anthropogenic effects of variation in landuse practices. Not surprisingly, total anthropogenic erosion

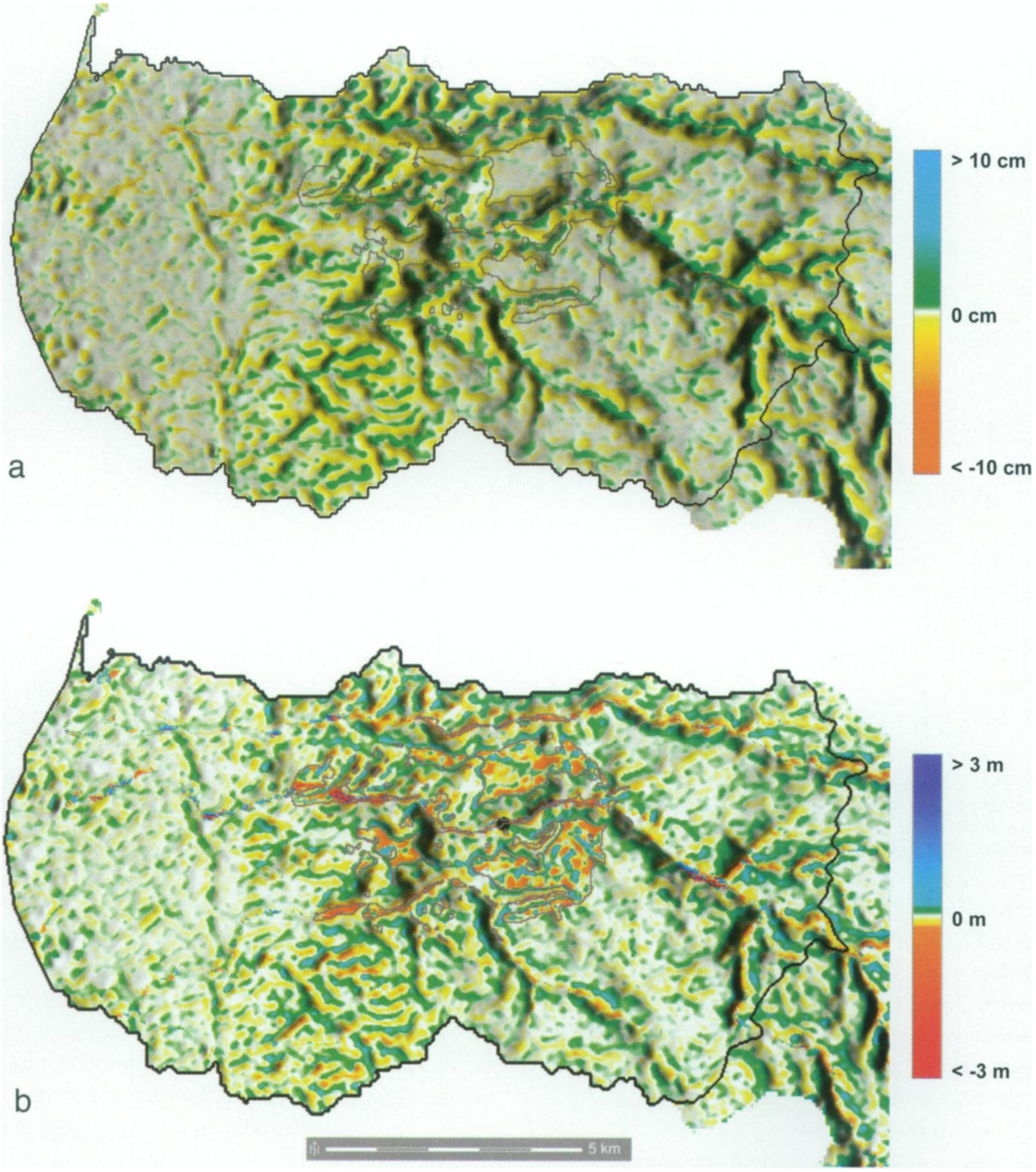

Figure 5. Map of modeled cumulative hillslope erosion/deposition (HED) for the Wadi Ziqlab watershed after 200 years. Upper map (a) shows HED without human landuse; lower map (b) shows HED due to human landuse, after subtracting 'natural' surface change from surface change with shifting cultivation and grazing. Scale is in meters of erosion or deposition of accumulated sediment. Agropastoral catchment boundaries shown in Figure 2b are outlined on both maps.

is generally higher for a village like Tell Rakkan, whose larger population cultivates and grazes more land, than for a hamlet like Tabaqat al Bûma for all modeled scenarios (Figure 6). But while shifting cultivation with grazing always produces the most anthropogenic erosion and intensive cultivation with no grazing always produces the least anthropogenic erosion, there is interesting variability between the other two scenarios that hints at potential differences of scale for the ecological impacts of human landuse. The large shifting cultivation catchment of the village dominates anthropogenic erosion; landuse scenarios that include shifting cultivation produce more erosion than do scenarios with intensive agriculture *irrespective* of whether or not grazing is included. At the hamlet, however,

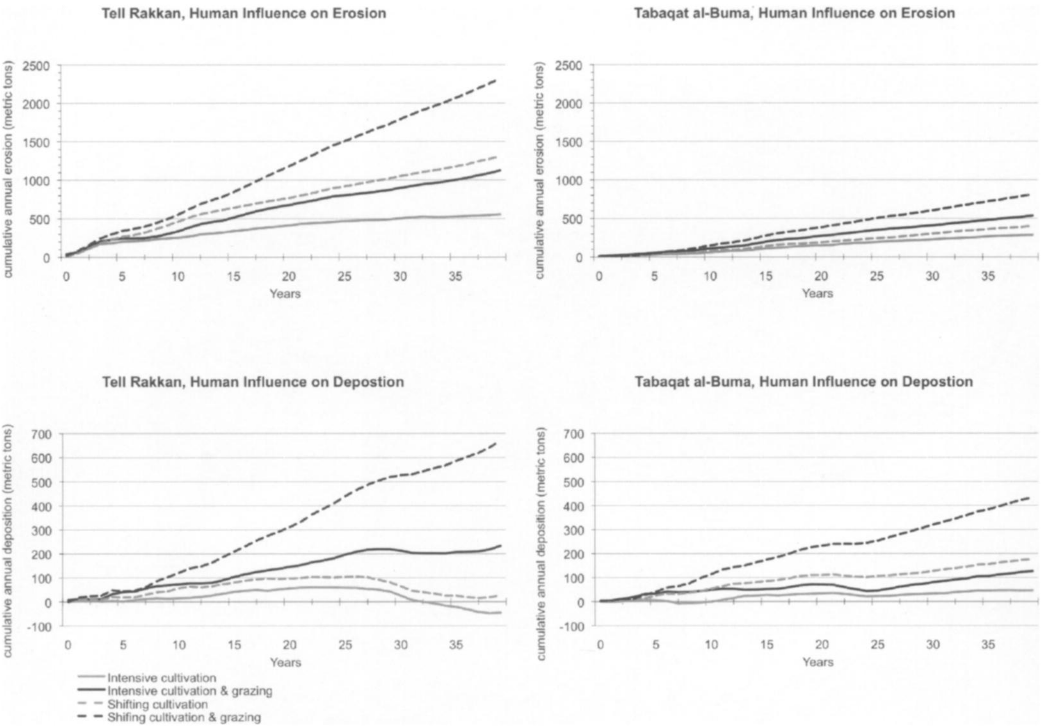

Figure 6. Cumulative anthropogenic hillslope erosion/deposition (HED) over a series of 40-year model runs for each experiment. Each point on each curve represents the mean of 10 repeated runs of each experiment minus the corresponding control model (i.e., without human landuse) values. Positive values indicate more erosion or deposition than would occur naturally, and negative values indicate less erosion or deposition than would occur naturally.

the shifting cultivation catchment is much smaller and has much less impact on total human-induced erosion. Grazing is the critical factor for this small settlement; scenarios that include grazing have the highest rates of anthropogenic erosion *regardless* of the type of cultivation practiced.

These modeled scenarios suggest a threshold effect in which the rate of anthropogenic erosion is more sensitive to the presence of grazing around very small settlements but becomes more sensitive to shifting cultivation as hamlets grow to village size. In part, this may be because a small hamlet like Tabaqat al Bûma can meet nutritional needs by cultivating only on the terraces and alluvial soils of the wadi bottoms (Figure 2), which are geomorphically dynamic with or without human alteration. Larger villages like Tell Rakkan, however, must expand cultivation to the upland areas bordering the wadi—especially for shifting cultivation—exposing areas to anthropogenically induced erosion that would otherwise be comparatively stable geomorphically without human impacts (Figures 2 and 5).

As with erosion, the maximum deposition (Figure 6) occurs with a combination of shifting cultivation and grazing, while the minimum is found for intensive cultivation and no grazing. For the village, however, scenarios that include grazing result in higher levels of deposition, whereas at the hamlet scenarios that include shifting cultivation produce more deposition. In other words, the rate of human-induced *deposition* is more sensitive to shifting cultivation around smaller sites, and more sensitive to grazing around larger sites. This is more difficult to explain and may need additional experimentation to clarify. One possibility is that while shifting cultivation generally contributes more sediment to be transported and deposited than other conditions, grazing does not produce excessive deposition until the area grazed passes some size threshold.

Comparing the model outputs from experiments

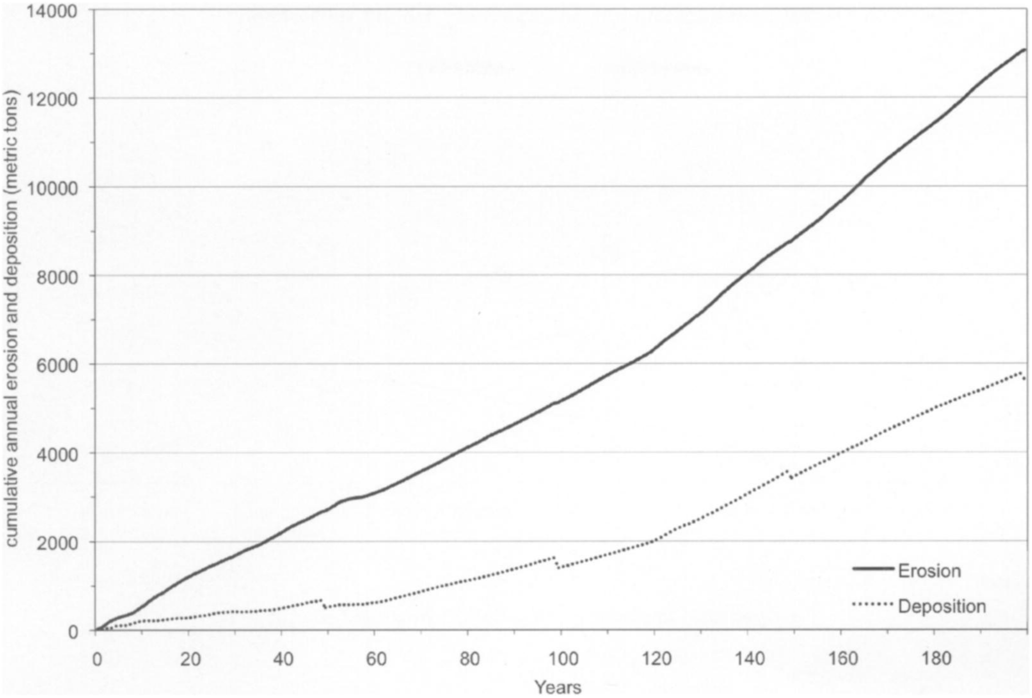

Figure 7. Cumulative anthropogenic hillslope erosion/deposition (HED) over a single 200-year model run for shifting cultivation with grazing model around Tell Rakkan.

from the two sites reveals another significant pattern. Total erosion for the entire watershed varies much more than total deposition between the catchments around the two sites (Figure 6). In fact, the highest cumulative anthropogenic erosion curve generated by the Tabaqat al Bûma catchment (shifting cultivation with grazing) is roughly equivalent to the lowest cumulative erosion curve for the Tell Rakkan catchment (intensive cultivation with no grazing). Furthermore, cumulative erosion rates for the Tell Rakkan experiments differ to a much greater degree from deposition rates than does erosion and deposition for the Tabaqat al Bûma experiments. Cumulative anthropogenic erosion in the watershed after 40 years of shifting cultivation and grazing around Tell Rakkan is 2317 metric tons, while cumulative anthropogenic deposition is 671 tons; similar experiments around Tabaqat al Bûma produce cumulative erosion of 813 tons after 40 years, and cumulative deposition of 432 tons. In other words, for combined shifting cultivation and grazing, deposition is over 50 percent of erosion for a small hamlet but drops to 29 percent of erosion rates for a small village. As discussed below, this offers important insights into the recursive social and ecological dynamics of early agriculture.

Finally, in order to examine differences between short-term (two generations) and long-term (10 generations) landscape effects of landuse, we calculated cumulative and deposition erosion values for one model run of 200 cycles (Figures 5 and 7). As mentioned above, we chose a scenario of shifting cultivation with grazing for a village like Tell Rakkan for this long-term test. There are two notable features of the HED curve in Figure 7. First, the rates of both erosion and deposition continue to increase over time. At least for the 200-year simulation, geomorphic surface change does not reach stability with continued agropastoral landuse. Second, the divergence between erosion and deposition, already larger for the village than for the hamlet, continues over time.

Vegetation Dynamics

Figure 8 displays the variance (CV) in area occupied by each vegetation class over the course of a

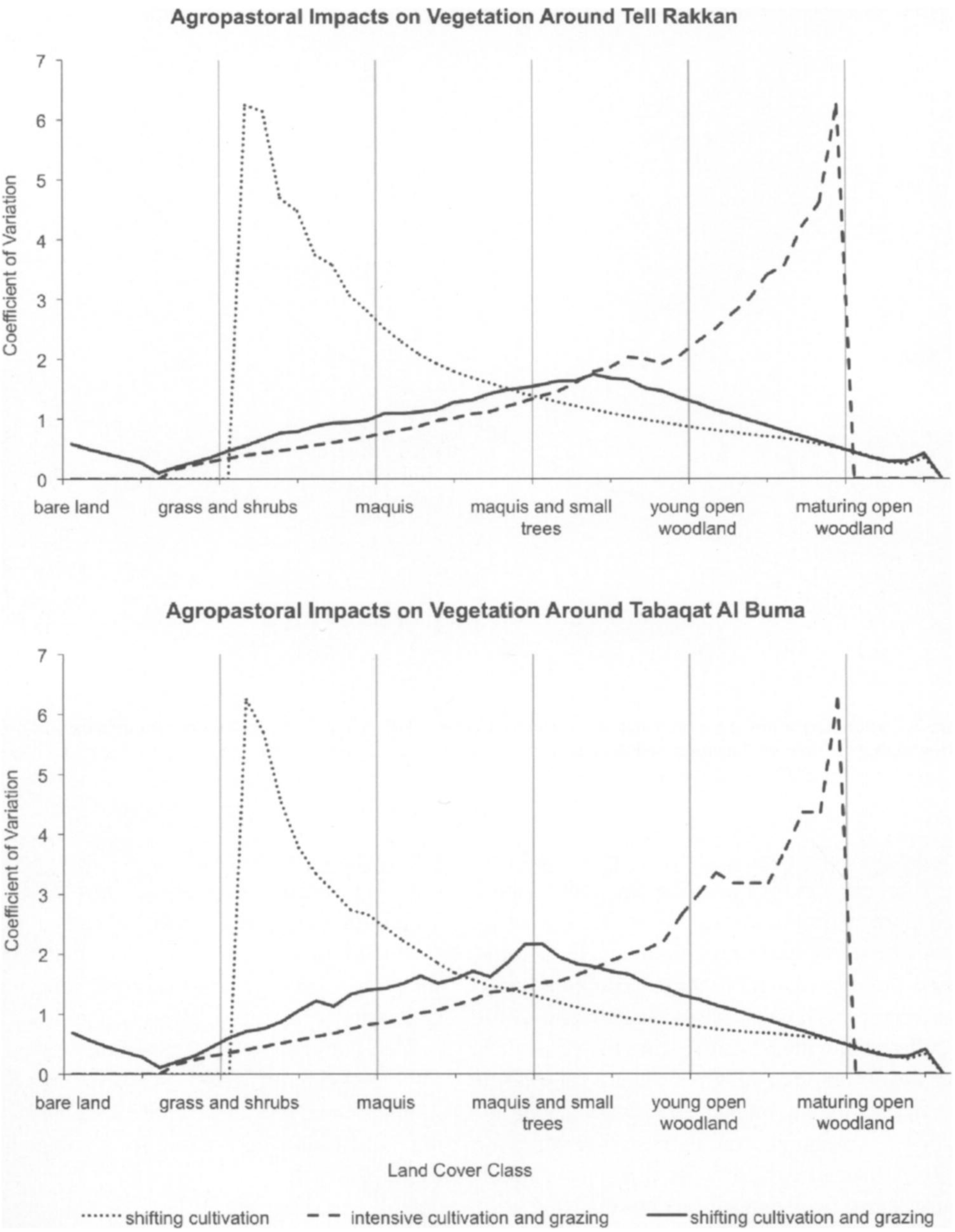

Figure 8. Coefficient of variation in the total area occupied by each vegetation class over a series 40-year experiments for Tell Rakkan and Tabaqat al-Bûma.

suite of 40-year experiments. Unlike the HED results, the effects of agropastoral landuse on vegetation display a very similar pattern for both settlements, even though the scale of landuse activities varies. Different landuse practices affected vegetation in very distinct ways, however.

- Intensive cultivation alone displays no variation through time because, once plots are cleared for cultivation and planted, they remain so. When grazing is added to intensive cultivation, the grazing (but not intensive cultivation) will produce variation in vegetation communities over time.
- Shifting cultivation without grazing produces a

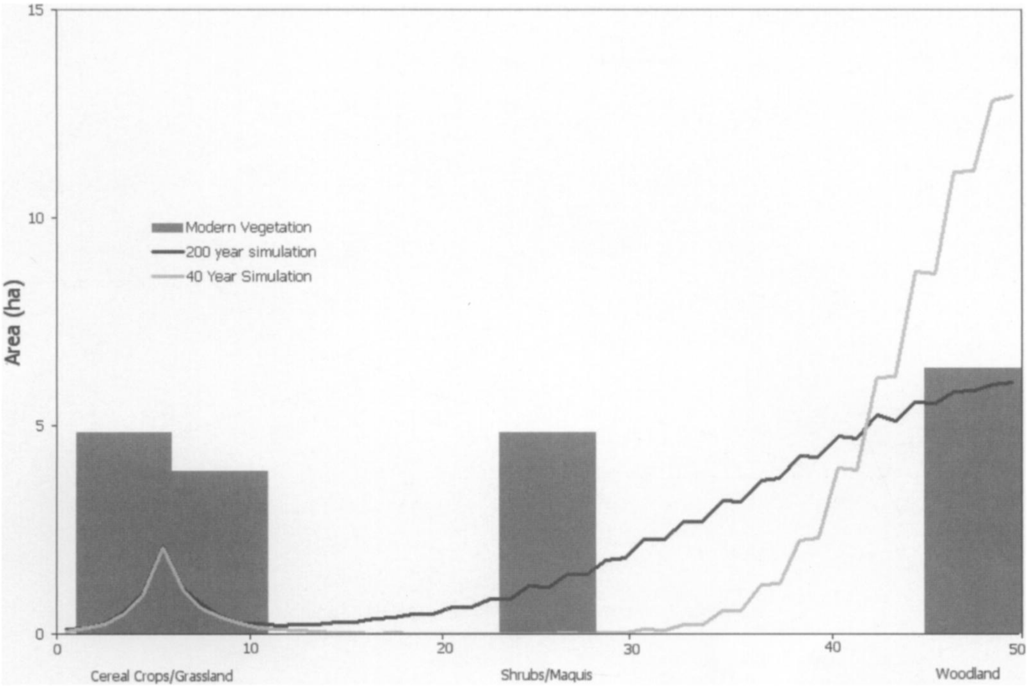

Figure 9. Total area occupied by each vegetation class after 40-year and 200-year experiments for shifting cultivation with grazing model at Tell Rakkan. Modern vegetation data for comparison derived from classification of Landsat TM imagery in the Wadi Ziqlab drainage.

profile with a high variation through time in the extent of grasslands, with human impacts on vegetation declining to the right, through shrub/maquis and woodland.

- Intensive agriculture with grazing produces a profile with of high variation through time in the extent of woodland, with declining variation to the left through shrubs/maquis and grassland.
- Shifting cultivation with grazing has the greatest impacts on shrub communities over the span of forty years, with declining effects on open vegetation and woodland.

In other words, shifting cultivation alters the landscape from the bottom up. Clearance for cultivation removes all land-cover from fields, which have limited plant cover until the field is abandoned. In fallowed fields open vegetation is slowly replaced by shrubs and ultimately by woodland, unless the field is cultivated again. Uncleared areas remain in woodland. Conversely, pastoralism alters the landscape from the top down. Domestic animals gradually reduce the existing land-cover over a larger area by grazing (rather than clearing) patches. With continued grazing, woodland is replaced by shrubs, open vegetation, and ultimately bare ground.

When shifting cultivation is combined with grazing, it produces a profile that is distinct from the other two types, with the greatest variation in vegetation extent occurs in the shrub/maquis group. Combining both "top-down" and "bottom-up" landscape alteration patterns, fallowed fields regrow toward shrubs and woodland is grazed toward shrubland. Significantly, this type of profile characterizes vegetation communities that dominate the Mediterranean region today—mostly scrub/maquis with some interspersed open woodlands and grasslands (Figure 9). This supports the suggestion that modern Mediterranean vegetation communities are largely anthropogenic, and that they are created and maintained by a combination of shifting agriculture with moderate fallow cycles and extensive grazing (e.g. Butzer 1996; Osem et al. 2002; Perevolotsky and Seligman 1998). Moreover, in our experiments, a combination of shifting cultivation and grazing created the most diversity in vegetation, with moderate variance spread

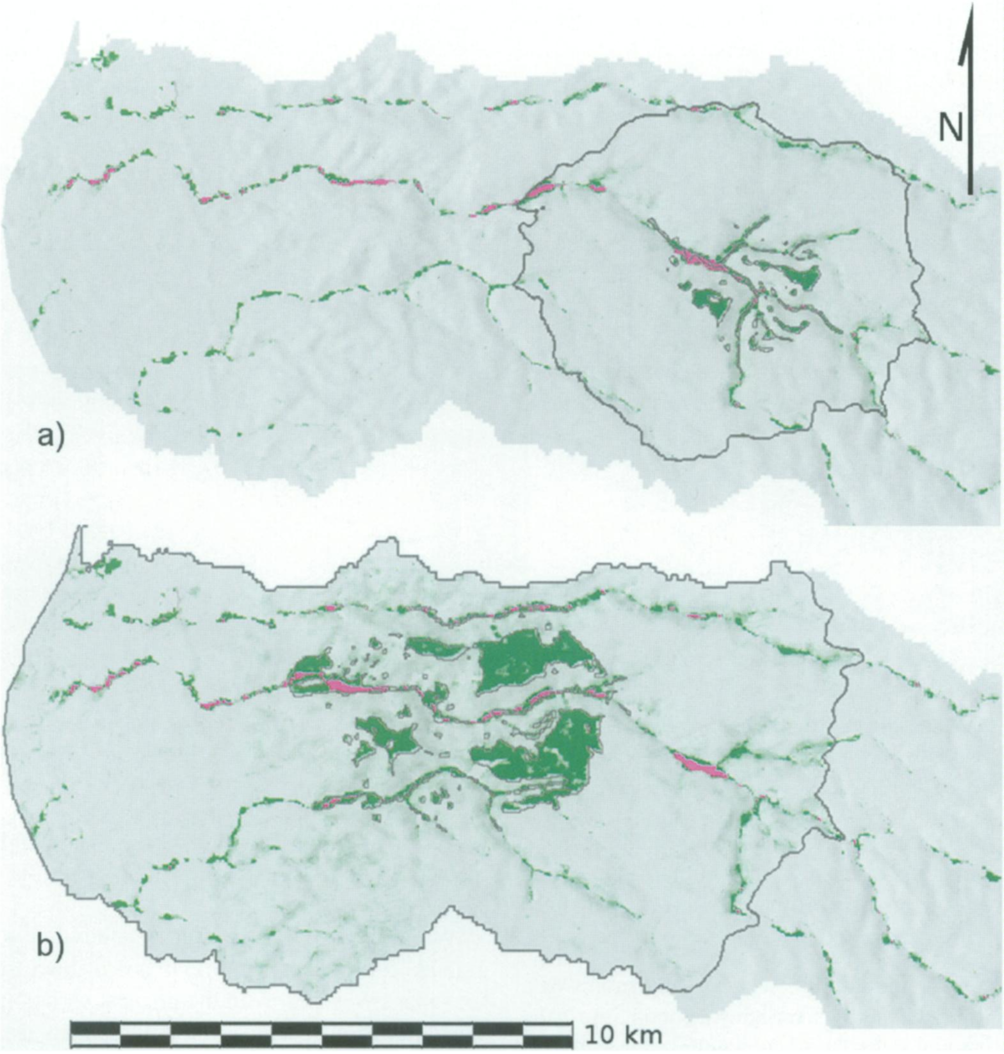

Figure 10. Mean anthropogenic variance in annual net hillslope erosion/deposition (HED) over 40 year experiments for shifting agriculture and grazing at Tabaqat al-Bûma (a) and Tell Rakkan (b). Red=high, green=moderate, grey=none.

widely across vegetation classes (Figure 8). Empirical study of the effects of light caprine browsing of Levantine flora also indicate that it *increase* species diversity (Osem et al. 2002). It is often unappreciated that while human landuse sometimes decreased biodiversity, in other circumstances it can enhance biodiversity.

Additional temporal dynamics of combined shifting cultivation and grazing can be seen by comparing the results of the short-term and long-term simulations. Figure 9 shows the total area occupied by each vegetation class after 40 years and 200 years of shifting cultivation and grazing in the catchment around Tell Rakkan. In the 40-year vegetation curve, patches of grassland and other fallow vegetation have spread due to cultivation and some of the forest has been reduced due to grazing, but shrub communities remain rare. After 200 years, however, the vegetation profile is remarkably similar to the profile of modern vegetation—dominated by shrub/maquis and degraded woodland, with patches of cultivated and fallowed fields. In other words, two generations of landuse decisions—a more clearly remembered time-span in preliterate societies—resulted in minimal, gradual changes to land-cover and gradual (even predictable) changes to surface soils and sediments. Only after 200 years—well into the legendary past of social memory for preliterate societies (McIntosh 2000)—has land-cover been transformed dramatically.

Discussion

Using computational modeling as an experimental laboratory offers new insight into the interactions between the landuse practices of subsistence farmers and their environments, the variations in these interactions across space, and their changes through time. This perspective on long-term socioecological dynamics that is not easily accessible through inferential reconstruction of the past from the static archaeological record alone, and offers the potential to better understand Neolithic farming and its consequences.

The experimental modeling presented here indicates that for small hamlets there is a balance between erosion and deposition that is potentially beneficial to farmer/herders. While agropastoral practices do cause erosion, and consequently the loss of potentially productive land, the greatest amount of erosion is a result of upland grazing; soil loss is concentrated in uncultivated lands and has little direct impact on their ability to sustain domestic animals. The other impact of grazing in the catchments of small hamlets, on the other hand, is to increase deposition in wadi bottoms—primarily from the erosion of the nutrient rich A and B horizons on slopes above wadis. That is, for hamlets like Tabaqat al Bûma or single farmsteads, the most deleterious effects of agropastoral landuse practices are concentrated in areas that have little economic impact on farmer/herders, and the most beneficial effects are concentrated in areas where they will have the greatest economic impacts. Furthermore, given the parameters of our experiments, the amount of potentially beneficial deposition can exceed 50 percent of the amount of nondeleterious erosion. In such circumstances, the economic benefits of mixed shifting cultivation and grazing should encourage expansion of these activities—and probably demographic expansion as well.

However, as communities grow, the spatial and economic consequences of mixed shifting cultivation and grazing change as well. At the size of small villages like the PPNB Tell Rakkan, shifting cultivation, not grazing, is responsible for most erosion. Moreover, soil loss occurs in areas where it degrades land in cultivation. Clearing and cultivating more land to compensate for this degradation only exposes more productive land to potential soil loss. As with the tiny hamlet, grazing can increase productive capacity through redeposition of eroded A and B horizons, but the expansion of grazing around villages increases deposition at a considerably lower rate compared with erosion than is the case for small hamlets. In the experiments carried out here, the deposition rate around small villages like Tell Rakkan is only 29 percent of the erosion rate after 40 years, and the deposition:erosion ratio remains low for at least two centuries. For small villages, then, the deleterious effects of agropastoral landuse now occur in areas where they have significant economic impacts, and beneficial effects occur at a low and declining ratio to deleterious impacts. Finally, the rate of erosion does not stabilize in experiments of small village agriculture and grazing, but grows over the long-term; after 200 years, over three meters of soil has been lost in some areas due to agropastoral landuse (Figures 5b and 7). The current experiments do not allow us to say precisely when this "tipping point" in the ecological consequences of landuse occurs, but the fact that it is apparent in the growth from a tiny hamlet to a small village (rather than an urban center) indicates the sensitivity of landuse-landscape dynamics to relatively minor changes in agropastoral practices. Though often unrecognized in archaeological inferential reconstructions, this kind of threshold behavior is typical for complex adaptive systems (CAS) (Bentley and Maschner 2003) of which human socioecological systems are exemplars.

Not only are the kinds of dynamics portrayed here by computational modeling difficult to demonstrate by typical archaeological methods, they would likely be equally inscrutable to subsistence farmers whose practices drive these processes. Farmers in small hamlets who expand both shifting cultivation and grazing, benefit by immediate returns of greater agricultural production and also by an expansion of productive capacity in the form of more fertile soil to cultivate in the future. Simultaneous increases in nutritional returns and future capacity favor demographic expansion in successful farming communities. Furthermore, significant changes are not immediately apparent in regional vegetation, and erosion/deposition rates increase but slowly within the span of living memory. Even the most conscientious and forward thinking farmer/herder would have no reason to change landuse practices.

At some point, however, the same landuse practices that made a growing village successful result in the increasingly rapid loss of its subsistence base. The immediate trigger could be the clearing of a series of new fields or a minor change in weather patterns, but the underlying shift in the equilibrium of human-environmental interactions would not be apparent to farmer/herders "on the ground." Their most likely immediate response to the perceived declines in productivity would be to expand the previously successful landuse practices—ones that now have increasingly deleterious consequences for at least some members of society.

Ultimately, two alternative "solutions" to anthropogenic degradation around growing villages are suggested by our modeling results. One is simply to disaggregate back into small hamlets. The other is to reorganize the landuse system to emphasize animal grazing over cultivation. Grazing has less immediately deleterious effects on agropastoral production and provides relatively more benefits to a subsistence system with a reduced agricultural component. This may be an impetus for specialized pastoralism among some social groups.

If we compare the results of computational experiments in socioecological dynamics of subsistence agropastoralism with the archaeological record, the broad outline of Levantine Neolithic prehistory follows the scenarios described above. Farming initially spread across the Levant in the context of small Pre-Pottery Neolithic A hamlets. This was followed by the expansion of some of these into small villages like Tell Rakkan and to much larger villages like 'Ain Ghazal in the Pre-Pottery Neolithic B (Simmons 2007). By the later Pre-Pottery Neolithic C and early Pottery Neolithic, most of the large villages were abandoned and human settlement was again distributed in small hamlets like Tabaqat al Bûma. The earliest evidence for specialized pastoralism is equivocal, but there are suggestions that this kind of economic specialization also began near the end of the Neolithic (Legge and Harris 1996; Martin 1999; Quintero et al. 2004; Rollefson and Kohler-Rollefson 1992; Rosen 2008; Twiss 2007).

Of course, there is also a third "solution" not yet explored in the modeling experiments reported here. In order to counteract the loss of general productivity due to changing patterns of anthropogenic effects on the landscape, some social groups might invest more labor into agropastoral systems, as well as intensifying production by terracing slopes and using plows. Because the deleterious impacts of expanding agropastoral landuse do not affect all villagers equally, social entrepreneurs could transform consequent wealth differentials into labor to accomplish such intensification more easily. Figure 10 shows the stochastic variation in net HED around both sites over the course of the 40-year simulations for combined shifting cultivation and grazing. This variation essentially measures farming risk—the difference between having a field with predictable returns or one that periodically experiences significant soil loss. Over the course of two generations, such risks become more pervasive, extensive, and intensive around the small village than around the hamlet. If any form of stable land tenure exists, the increased risk differentials around larger villages that result from shifting landuse-landscape interactions can lead to long-term economic inequalities among households. In fact, increased ecological and subsistence risk may favor the emergence of land tenure, as households with more predictably productive lands seek to pass on control of such lands to their descendents. A frequent outcome of such economic differentiation is that wealthier and more ambitious household can gain access to additional labor from poorer households because of accumulated subsistence (and other) debt. This gives these more powerful households the productive means to intensify agricultural landuse, accumulate landesque capital, and expand sociopolitical power. Again, the general outline of Levantine prehistory, as it is now known, indicates that such intensification of landuse and its consequences occurred by the end of the Neolithic in some settings. The rest, of course, is history.

Concluding Comments

An experimental approach that incorporates computational modeling has allowed us to propose alternative scenarios of long-term landuse-landscape dynamics for subsistence farming and compare them with the archaeological record. We use a stochastic approach to modeling landuse practices. But in fact, such practices are a behavioral consequence of decisions that combine perceptions of the environment, allocations of labor, assessments of economic costs and benefits, along with traditional knowledge and belief systems. Human-decision making also can be explored through computational modeling (Axtell et al. 2002; Christiansen and Altaweel 2006; Kohler et al. 2005). We are developing an agent-based simulation module of farming households for future versions of the LLD laboratory that will be coupled with the landscape model discussed here (Mayer and Sarjoughian 2007) to further study LLD from the point of human decision-making (Axtell et al. 2002; Bankes et al. 2002; Janssen et al. 2003; Johnson et al. 2005). This will give us more robust tools to conduct further experiments on the recursive effects of socioeconomic decision-making at the level of households or individuals, including further testing the scenarios proposed here.

Nonetheless, even the relatively simple stochastic algorithms used in this paper to represent spatially and temporally varying human landuse practices, still hold considerable potential for archaeological research on long-term human socioecology. While the correspondence between our experimentally derived socioecological dynamics and the inferential archaeological record is encouraging, we also hope that the collection of geoarchaeological data planned and in progress, along with the testing of experimental results in different settings (e.g., eastern Spain) will provide more robust validation and tuning for our models.

As we indicated at the beginning of this paper, archaeologists have done a remarkable job of wringing information from a highly degraded and largely missing record to create compelling narratives of the human past. A goal in much of the theoretical literature of the field for the past four decades has been for archaeology to build a scientific understanding of long-term human change through the cumulative development and replicable, transparent testing of explicit, quantitative models of complex human social and ecological processes. But much actual archaeological research has fallen short of these lofty goals, in spite of ever more sophisticated methods for data collection. Recent literature suggests that some archaeologists understandably seem to despair of ever realizing such goals. Computational modeling techniques that are now widely available—including those described here—offer an exciting new opportunity to revitalize a scientific archaeology without sacrificing the complexities of culture and practice that make the study of the human past so fascinating both to practitioners and the public. The potential for a scientific archaeology that can create and empirically test explicit, transparent models of human social and ecological dynamics is also timely given the renewed interest, both within the field and more importantly beyond the field, in the contributions that archaeologists can make to other social and natural sciences, and more broadly to social decision-making today. While archaeologists will continue to craft compelling narratives, we look to a future where these narratives are based on theoretically informed, explicit, computational models that form the historical framework for a science of social dynamics.

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Notes

1. The one-dimensional stream power equation uses a value of slope = dz/dx. However, Moore and Burch (1986) suggested using the sine of slope (used by USLE and sheer stress equations) to expand this to a two-dimensional landscape.

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