# Modeling Long-Term Landscape Dynamics and the Emergence of Intensification

C. Michael Barton[1], Hessam Sarjoughian[1], Steven Falconer[1],
Helena Mitasova[2], Ramón Arrowsmith[1], & Patricia Fall[1]

*Society for American Archaeology*
*70th Annual Meeting, April 2006*

*Draft*
*Please do not reproduce or cite without author permission*

## ABSTRACT

*Archaeologists have focused on reconstructing the past in ever more sophisticated ways since the inception of the discipline. However, this research strategy may no longer be sufficient to address new challenges facing the discipline. A complementary strategy is to use the past as a laboratory for testing dynamic models of socioecological process. The study of agricultural practices in particular can benefit from this approach because they have direct and indirect, long-term consequences on landscapes that vary in intensity, time, and space. We are developing a modeling laboratory for characterizing interactions between agricultural practices and landscape change for the Mediterranean Basin. Here, we report on initial work that integrates agent-based models of village farming and GIS-supported surface process models to capture the long-term dynamics of socioecological landscapes.*

## ARCHAEOLOGICAL RESEARCH STRATEGIES

Since its inception as a discipline, archaeology has focused its primary research strategy on increasingly sophisticated reconstructions of past societies, events, and processes. There have been recent calls, however, for archaeology to play a more significant role in discussions of modern social and environmental policy (Redman and Kinzig 2003; van der Leeuw and Redman 2002). Indeed, with its unique command of the multi-millennial, global span of the human past—and in many cases the broader context

---

[1] Arizona State University
[2] North Carolina State University

of social action—archaeology offers a potentially valuable perspective on the outcomes of human decisions in diverse social and environmental settings. Yet, so far, archaeology's primary contribution to a broader understanding of social dynamics has been in the form of compelling, but anecdotal case studies.

In order for archaeological insight to serve as an effective guide for policy, and not simply provide cautionary tales, however, we as archaeologists may need to embrace new research strategies. One such strategy involves developing quantitative and spatially explicit models of human decisions and testing the results of such models against the archaeological record at various temporal and spatial scales. This has especially promising potential for understanding the recursive interactions between social landuse decisions, climate change, and landscape dynamics at regional scales.

The Mediterranean Landscape Dynamics project, along with a handful of other ongoing projects (Kohler, et al. 2005; Kohler and Johnson 2004; Wilkinson, et al. 2004), is endeavoring carry out such a research strategy. We are creating a modeling laboratory to evaluate the long-term effects of differing landuse practices on landscapes and society, using the Mediterranean Basin's rich archaeological and paleoenvironmental record to develop, validate, and tune the models. We report here on the current status of this project and the potential for creating a laboratory of the past to model human-environmental interaction. This is especially pertinent to understanding the processes and consequences of subsistence intensification on landscapes more generally.

## RECONSTRUCTING THE PAST: ISSUES WITH THE ARCHAEOLOGICAL RECORD

The reconstruction of past events and processes has long been a primary goal that has guided archaeological research. Over the past century and a half, we have developed increasingly sophisticated methodologies, technologies, and conceptual tools to do this.

But a survey of the articles that make up *American Antiquity* makes it clear that reconstructing the past remains at the center of most archaeological research today. Archaeology as a discipline has been highly successful at wringing bits of past lives out of the archaeological record. But we may be reaching a threshold at which the archaeological record is simply incapable of providing information that will allow us to reconstruct the past in sufficient detail to address the questions that we increasingly pose. This is especially problematic for understanding human-societies as integrated systems that operated at regional scales on past landscapes.

One difficulty is that, far from being a snapshot of past lives, the archaeological record is generally a jumbled hodge-podge of the unusable trash discarded by ancient people (Binford 1981). Especially at landscape scales, but also within stratified occupational settlements, the artifactual assemblages on which we rely to reconstruct past lives are usually palimpsests of refuse that accumulated over the course of many years or even generations (Barton, et al. 2002; Barton, et al. 1999; Barton, et al. 2004; Wandsnider 1992; Zvelebil, et al. 1992); except statistically, these palimpsests cannot be untangled into the multiple records of the people that produced them. Furthermore, the archaeological record is a static one, whether a time-averaged accumulation or one of the rare cases where lives were stopped in mid-stream—usually by a catastrophe of tragic consequences for the people in question. Yet from these static collections of debris, we more and more wish to reconstruct the dynamics of individual action and social change.

Finally, the most troublesome issue for reconstructing regional systems—and the most insurmountable one—is most of the material record of past societies is simply unavailable. Most past material culture is simply gone—destroyed by taphonomic transformations—or buried beyond reasonable expectation of discovery and recovery. Of what remains and is potentially accessible, most has been moved variable (and at times very large) distances from its original place of discard (not to mention its place of actual use) and further mixed with other cultural remains. Of this, archaeologists have sufficient resources to collect only a small fraction and analyze an even smaller fraction in detail. Even in some of the most intensively studied regions of the world, if we were to honestly ask ourselves how many artifact assemblages at regional scales derive from the activities of people who were even living at the same time, much less in the same week, month, or year and interacting socially, most archaeologists would be hard pressed to produce two such assemblages with any confidence (Barton and Neeley 1996). Yet, as our discipline matures, our theory and research questions often center on the interaction and social practice of the day-to-day operation of societies. It is a testament to the perseverance and abilities of archaeologists that we have been able to create such credible reconstructions of the past with such minimal and poor information.

These limitations of the archaeological record are well known and have been discussed in the literature for decades. Nevertheless, many carefully-designed, scientifically conducted, and well-written archaeological research projects are carried out as if these issues do not matter for reconstructing the past. If we are simply speaking to each other or creating plausible stories for a curious lay public, perhaps they do not. However, if archaeology is to have a significant role at the center of an interdisciplinary science of humanity, then these issues do matter. Archaeology has the potential to lead research on the long-term dynamics of human systems, the consequences of human-environmental interactions, the co-evolution of human biology and society, and other equally large and compelling topics. It has the potential to apply the knowledge of long-term change to inform policy on the future consequences of social policy (Morrison 2006; van der Leeuw and Redman 2002). Yet, how can we claim to understand the social dynamics and its outcomes when most of the record for reconstructing past systems is missing or unrecovered, and the remainder is static trash? Our data and methods are simply insufficient for such goals if we continue to focus our efforts on reconstructing the past from the archaeological record.

## A LABORATORY OF THE PAST: AN ALTERNATIVE TO RECONSTRUCTION

An alternative, but complementary research strategy is to use the long, rich, and diverse human past as a laboratory to study social and ecological processes. The basic protocols of this approach to:

- build on accumulated archaeological and anthropological insights to develop dynamic computer simulation models of social and ecological processes;
- treat these models as complex hypotheses; and
- test these hypotheses against the archaeological record.

Rather than being a source of information about past lives and societies, the archaeological record then becomes a rigorous test-bed for validating dynamic models of social process, offering an opportunity to evaluate such models in diverse contexts and study outcomes at different temporal and spatial scales. Only the most robust and reliable models will have results that consistently pass through the sparse and spatially and temporally discontinuous points of the archaeological record. In this way, the very characteristics of the record that are problematic for reconstruction can better serve to validate models of social dynamics.

The idea of hypothesis testing in archaeology is not new, of course, having been advocated for nearly a half-century. However, it has been hampered by conceptual and practical difficulties in framing non-trivial hypotheses about complex social processes in an explicit and quantitative form that could be adequately tested against the archaeological record. This has been compounded by the difficulty in testing hypotheses about process and social change against an archaeological record of static moments in the best of circumstances, and time-averaged accumulations of such moments more often. But recent advances in computer technology, especial in social and geospatial modeling, provide a new opportunity to put this kind of approach into practice.

A 'laboratory of the past' research strategy offers additional benefits to the discipline of archaeology beyond a new way to approach challenging questions of the 21st Century. It is complementary to the long established reconstruction-focused strategy, using insights gained from more than a century of such work as a basis for model building, and employing reconstruction-based interpretations of archaeological data to establish the spatially and temporally dispersed 'points' needed for model evaluation. It also gives us a chance to replace the ever-speculative interpolation, by which we fill the gaps in the archaeological record with narrative, with the results of explicitly and quantitatively developed dynamic models. Importantly, this makes it a more straightforward exercise to evaluate the efficacy of alternative models in accounting for the facts of the archaeological record and probable causal relationships of system dynamics, rather than relying on the literary skills of a researcher to tell a more convincing story.

## THE MEDITERRANEAN LANDSCAPE DYNAMICS PROJECT: CREATING A LABORATORY OF THE PAST

The Mediterranean Landscape Dynamics project, sponsored by the NSF ERE Biocomplexity in the Environment Program (BCS-0410269), is working to put this kind of research strategy into practice, creating a modeling laboratory for studying the social and ecological consequences of landuse practices in the Mediterranean. A primary goal of the research to be conducted in this laboratory of the past is to gain a better insight into the recursive interactions of humans and landscapes at multiple temporal and spatial scales, including the transition from household gardening to intensive agriculture. We use the term socioecosystem (and its derivative, socioecology) to refer to the complexly coupled human and natural ecosystems that have arisen in the Mediterranean and elsewhere during the Holocene. In brief, we aim to couple agent-based simulations of human landuse with geospatially explicit geomorphic surface process models for landscape change, high resolution synoptic climate models, and spatially explicit models of natural and anthropogenic vegetation. We are using the rich archaeological and paleoenvironmental records of the early to mid-Holocene in study areas in eastern Spain and western Jordan as a test bed for developing, validating, and tuning dynamic models of long-term socioecology (Figure 1). These regions encompass much of the range of social and environmental variability across the Mediterranean region. Our modeling interval spans the beginning of agropastoral socioecosystems (about 10,000 bp in Jordan and a little after 8,000 bp for Mediterranean Spain) to the beginning of urban civilization in the early Bronze Age (ca. 4,000-5,000 years ago). This interval includes the shift to dependence of food production and the beginnings of agropastoral intensification. Below, we describe the organization of this project and present an overview of the components of this modeling laboratory we have completed in this early stage of the research.

## BUILDING A MODELING LABORATORY

The modeling laboratory we are building to study the outcomes of human landuse practices includes three components (Figure 2). The main component is a model for the long-term dynamics of **agropastoral socioecology** in the Mediterranean. This component is where we will study the interactions of social practices and landscapes to investigate questions of agricultural dispersal, intensification, and sustainability. This includes an agent-based modeling platform to simulate human landuse decisions and practices, coupled to geospatial surface process models that simulate landscape change, especially differential erosion and deposition. High-resolution climate models provide inputs to both the agent and surface process components. Landcover (initially vegetation, but eventually to include soils) is modeled on the basis of topography, climate, and human landuse, and in turn affects both surface processes and landuse decisions. Each of these sub-components are discussed in more detail below.

A second component to the modeling laboratory is a **potential landscape** model. This is similar to the agricultural socioecology model but without anthropogenic landcover change generated by the agent-based landuse simulations. That is, it includes surface processes models, climate model input, and landcover with the same kinds of feedbacks among these components as described above. The potential landscape model offers a baseline against which to evaluate the spatial and temporal effects of the human component of Mediterranean ecosystems.

The final component to the modeling laboratory is a **sequence of biophysical and cultural landscapes** interpolated from the archaeological and paleoecological records of both study regions. These landscape sequences do not comprise a dynamic model in the sense of the other two components, but are inferences based on diverse data collected during decades of research. Because these landscape sequences are reconstructed from the archaeological and paleoecological records, they are necessarily discontinuous in space and time, as noted above. We will use these for validating and tuning our dynamic socioecology models. That is, the output of the dynamic models will need to approximate site distributions, sediment accumlations, and vegetation change, for example, as inferred from the archaeological, geological, and palynological records. The reconstructed reference landscapes also can be compared with temporally and spatially corresponding output from the dynamic potential landscape model to more quantitatively assess the extent of anthropogenic change in both regions.

We began the work of building a laboratory of the past for modeling Mediterranean socioecology in the Fall of 2005. After nine months of work, we now have operational prototypes of most subcomponents—digital topography, high-resolution climate, erosion/deposition dynamics, and agent-based landuse—and the remainder are in progress. We describe these prototypes here, to provide colleagues with a better idea of the nature of work involved with implementing a laboratory of the past research agenda, to illustrate the potential benefits of this kind of research, and because the subcomponents we have developed to date may prove useful as stand-alone tools for other researchers interested in the landscape consequences of changing landuse practices.

## TOPOGRAPHY

For regional-scale topography and spatially explicit climate models, we are using digital elevation models (DEMs) produced from the Shuttle Radar Topography Mission (SRTM) in February 2000 < http://srtm.usgs.gov>. SRTM DEMs are available for all the earth's land surfaces between 60° N and 56° S. The data were gathered at a ground resolution of 30m. They are available at this resolution for the United States, and at a resolution of 90m for the rest of the world, at no cost from several internet sites.

For topographic base maps, landcover, and erosion/deposition modeling, we are using higher-resolution DEMs produced from Terra ASTER satellite imagery (Figure 3). ASTER is a collaborative project between NASA and the Japanese Ministry of Economy, Trade, and Industry < http://asterweb.jpl.nasa.gov>. Terra ASTER imagery is collected in 14 bands of visible light and infrared, with resolutions that range from 15-90m. Band 3 (15m resolution) is taken with forward and backward cameras that produce stereo imagery that can be processed into DEMs. ASTER imagery is available at low cost or no cost to qualifying researchers. To produce DEMs for more realistic erosion modeling in areas with convergent water flow, we interpolated these DEMs to a 10m resolution using spline methods (Mitasova and Mitas 1993).

For highest resolution topography, we are creating our own DEMs from stereo aerial photographs and Corona imagery. Corona panchromatic imagery was taken between 1960-1972 at resolutions of 2-8m, and was declassified in 1995. It is available at low cost. This very high resolution topography, especially, will be used for geomorphic mapping of Holocene land surfaces of different ages. We will then use spline- and TIN-based interpolation to recreate paleolandscapes at various times in the past for the reference biophysical landscapes mentioned above, and to serve as starting points for dynamic landscape modeling. The Holocene geologic history of the areas is inferred from detailed geologic mapping from aerial photography and compilation of field data and will be tested in the coming years with direct field checking.  We find that the modulation of climatic and anthropogenic drivers on the overall aggradation or incision of the geomorphic system results in the formation of stable terrace surfaces separated by meters to tens of meters of intervening incision. Each of these levels for now is correlated based on elevation and geomorphic form, and thus is interpolated to reconstruct the landsurface at that time. In addition, we can identify areas of rapid incision and mass movement that may indicate "hot spots" in the geomorphic system which we can cue on for detailed modeling.

## CLIMATE

Rather than using global circulation models (GCM), one of whose grid cells could cover an entire valley of our study region, we are using macrophysical, synoptic climate models (Arzt n.d.; Bryson and Bryson 1997, 1999; Ruter, et al. 2004). These offer offer modeled climate parameters at both high spatial and temporal resolution. The fine spatial scale is especially important, as it better matches the scale at which individuals and households made and enacted landuse decisions.

These models provide monthly and annual climatic parameters (mean temperature, days above 0° C, days below 40° C, total precipitation and precipitation intensity) at 200 year intervals, from 15,000 bp to the present, for a series of weather stations within each study region (Figure 4). We derive multiple regression functions to interpolate these climate values between the weather stations, creating spatially referenced climate maps for each region (Figure 5). This means that for every 30m or 90m grid cell of the landscape, we have estimated climatic parameters that affect local vegetation, runoff, and agricultural potential. Interpolating temperature has been relatively straightforward, simply using elevation and geographic coordinates. But precipitation has been considerably more complex, additionally involving distance from the Mediterranean coast, topographic aspect, and orographic values such as maximum elevation between a location and the coast. In spite of this complexity, we have been able to develop functions that can predict all weather station data with high accuracy (R values > 0.9), giving us confidence that our interpolations of climate between the stations are as reliable as the underlying models.

We have completed test modeling of climate parameters for northern Jordan and have the regression coefficients to model all the Jordan Valley and adjacent highlands. We just completed a script in GRASS that will allow us automate the generation of the hundreds of climate maps needed. The weather station models for eastern Spain were recently completed and we are ready to begin calculating regression coefficients for this region.

### LANDCOVER

We are in the process of developing models of potential vegetation for the region. We are taking two, complementary approaches: a top down and a bottom up approach. The top down approach involves using large-scale maps of potential vegetation communities such as those of Harowitz for the Levant (Harowitz 1979). These are matched with current topography and climatic parameters to produce mathematical functions (generally regressions, but also Boolean functions) that can then be applied to past climatic parameters. Examples of this kind of modeling can be found in Spikens (Spikins 2000). The result is maps of past distributions of Mediterranean vegetation communities based on climate and topography. The bottom up approach uses a similar protocol, but does so at the level of individual key plant taxa. Modeling the distributions of taxa instead of communities is more complicated, but offers the possibility of identifying plant associations that may have developed under past conditions but no longer exist. Recent work by Barboni (Barboni, et al. 2004), serves as a guide to computing such functions for predicting distributions of key taxa. Now that we have finished preliminary climate modeling, we can begin landcover modeling.

### LANDSCAPE DYNAMICS

We are taking a staged approach to building dynamic landscape models. Our initial efforts are directed at comparatively simple physical models of sediment entrainment, transport, and deposition (Table 1), including revised soil loss equation (RUSLE) and unit stream power erosion-deposition (USPED) (Mitasova and Mitas 1999, 2001a, 2001b). The better known RUSLE can provide information about erosion potential, hillslope detachment, gully locations, and averaged soil loss in watersheds (Hill 2000, 2006). USPED, however, offers the added potential to calculate net erosion or deposition at each point of a landscape (Mitasova and Mitas 1999). We also use these net erosion/deposition values to add or subtract elevation from a DEM, changing the landscape. We now have an iterative version of USPED (r.usped in GRASS GIS) that can accept R-factor values derived from a precipitation map and representing the impact of rainfall intensity on a land surface, C-factor values representing impact of different types of land cover (ratio of soil loss from land under specified conditions to the corresponding soil loss from bare soil), K-factor values representing soil erodibility, and a topographic factor (a function of upslope contributing area and slope) derived from a DEM; calculate net erosion and deposition rates; and alter a DEM to simulate terrain change (see <http://skagit.meas.ncsu.edu/~helena/gmslab/reports/cerl00/rep00.html> for more detailed information on modeling coefficients and methods).

Figure 5 shows an example of such change after a series of iterations in northern Jordan. For this example, we use simple, constants for runoff and landcover, rather than more complex modeled values. Relatively flat areas of the landscape (< 5° slope) totaling

34 ha were created as buffers around known Neolithic settlements in the Wadi Ziqulab to represent probable cultivated land (using averages of 1.36 ha ha of fields/person, 5 individuals/household, and 5 households/settlement, based on ethnographic and epigraphic evidence). Based on empirical work, a C-factor value of 0.5 was assigned to cultivated land. A larger buffer grazed land also was extended to 3 km around the settlements. For this example, we only classified 50% of the land as grazed (C-factor of 0.6 for 'degraded grassland'). Beyond this, the land cover remained Mediterranean forest/woodland, with a C-factor value of 0.01 (denser forests can have even lower values of 0.001-0.0001). An R-factor value of 60 was, equivalent to 'mild seasonal rain' typical of a Mediterranean climate.

Figure 5 shows the 10m resolution DEM before modification and after iterating USPED 10 times (roughly equivalent to 10 years). Areas of severe erosion are seen along the wadi margins, within the human modified areas. In other preliminary tests, grazed areas seem to have suffered considerably more intensive soil loss than cultivated areas, even though only 50% is classified as grazed and grazed landcover is slightly less susceptible to erosion than cultivated land. A possible reason for this is that grazing can occur at considerably steeper slopes than permitted for cultivation in our model runs. We will evaluate this outcome further as we develop the modeling laboratory.

Sediment eroded from slopes is being deposited in the wadi bottoms and mouth, although this is not obvious in Figure 5. Such areas may become more fertile and attractive for agriculture over time. This will affect decisions about where to cultivate, simulated in the agent model discussed below, changing the spatial organization of landscape dynamics. These are the kinds of interactions we plan to study as we begin to couple the modeling laboratory subcomponents.

As we expand dynamic landscape modeling from limited pilot areas of 100-150 sq km to the entirety of the larger, biophysically more diverse study regions, we may need to further enhance the USPED model to better reflect the spatial variability of surface runoff and its routing through the landscape, or switch to more complex, physics-based models such as the simulated water and erosion model (SIMWE) (Mitasova and Mitas 2001a, 2001b; Thaxton 2004). We will need to evaluate our results empirically to determine whether the results of these more sophisticated simulations are sufficiently better at matching the prehistoric record than USPED coupled to agent-based landuse to make them worth their more intensive computational requirements.

### LANDUSE DECISIONS AND PRACTICES

Human social systems are complex, and comprehensive simulations of such simulations must be equally complex (Christiansen and Altaweel 2004; Wilkinson, et al. 2004). However, the more complex the simulation, the more difficult it is to understand the interacting effects of multiple factors, and to evaluate the ability of a model to accurately simulate the processes desired. The recursive interactions between human landuse decisions and practices, landcover, climate, and geomorphic surface processes are likely to be highly complex. But because a significant portion of this system are governed by biophysical processes, we have a reasonably good chance of gaining valuable insights about the consequences of varying landuse decisions and practices under varying environmental conditions—although we cannot underestimate the challenge of doing so. If we were to attempt to include fine-grain details of social life—personal interactions, ideology, political and power relations—we could introduce higher-order interactions that may be difficult to understand, and confound already complex interactions between humans and landscapes that are the focus of this research. Further more, such intangibles, while extremely important aspects of human society, are much more difficult to model and validate against the material archaeological record. We do not rule out the potential value of simulating social processes more comprehensively, but initially at least, we plan to keep our laboratory comparatively simple by focusing primarily on landuse, while recognizing that even this comparative simplicity will generate a highly complex system (Figure 2).

We are developing the agent-based simulation in DEVS JAVA <http://www.acims.arizona.edu/>. This uses Java to implement a discrete event simulation highly flexible environment that has been used for social simulation (Zaft 2001; Zaft and Zeigler 2002). This platform also has the potential of being operated in a collaborative setting via a standard web browser. We have set the household as the basic simulation model unit, or agent (Figure 7). We recognize that individuals make decisions, but households generally operate as a single economic unit with regards to landuse in simple (and many complex) agrarian societies. Equating households and agents also means that we do not have to simulate the internal dynamics of households while still paralleling reality fairly closely. Households are organized into villages; that is, groups of households explicitly located in space and distinct from other village groups of households.

In this initial prototype especially, household agents engage in only very simple behaviors. Ethnographic studies and historical texts provide estimates used for initial parameters such as the amount of land a household needs to survive with subsistence farming, average household size, and numbers of households in villages (Allen, et al. 2006; Falconer 2005). We have developed time-dependent object-oriented agent models using the DEVS framework (Sarjoughian and Zeigler 1998; Zeigler, et al. 2000) to simulate households and their emerging behavior as they interact with the landscape (Mayer, et al. 2006).

A brief description shows how simple individual household dynamics and their interactions with the landscape can result in complex dynamics. Households can manage resources—limited to generic crops currently, but potentially including different kinds of crops, livestock, and other capital. Households also can obtain information about resources such as soil or the slope of a potential field, and can affect resources such as 'wild' vegetation through landuse practices. Household agents select land based on its potential productivity, distance from a village, and amount of labor investment needed to make the land productive (e.g., whether a tract of land needs to be cleared of woodland, cleared of fallow, or simply cultivated). Multiple households in a village compete for multiple tracts of land, each of which can have different combinations of productive potential, distance, and investment costs. In our initial prototype, this competition is a simple scramble at the beginning of each yearly agricultural cycle. As this 'land grab' proceeds, the relative attractiveness of a tract of land will change depending on which tracts have already been claimed.

The total return to each household at the end of each cycle depends on the amount of land it controls, the productivity of the land, and the cost to obtain agricultural returns. These returns, compared against household needs, contribute to decisions about the amount of land needed in the next cycle. If a household consistently cannot meet its needs, it declines and eventually ‘dies’. The productivity of a land tract also declines for each cycle it is cultivated. If it remains fallow for a cycle, it begins to regain fertility. However, it produces no agricultural returns while fallow. (No domestic animals are currently included in the simulation, although they will be introduced later).

In the prototype agent-model (Mayer, et al. 2006), the object-oriented Cellular DEVS module is used to simulate the landscape and spatially distributed resources. A primary reason for using DEVS was its built-in capability to integrate household agent models with cellular landscape models. However, we plan to use a GIS (GRASS <http://grass.itc.it>) to organize landscape information. A GIS-based modeling is optimized for storage and retrieval of very large geospatial data sets. Indeed, the procedure-based, modular execution of GRASS affords speeds many orders of magnitude faster than object-oriented Cellular DEVS. Furthermore, a GIS also has numerous built-in routines for complex geospatial management and analysis tasks that may not be necessary to develop in an object-oriented programming language. Linking an agent modeling platform to a GIS is highly desirable for the kind of socioecological research laboratory we are constructing for additional reasons. A GIS can easily represent diverse real-world landscape characteristics and translate them into forms usable by an agent-modeling platform. It also can easily scale up or down spatially, and manage complex coverages that represent large spatial areas. This makes it possible for a coupled agent-GIS model to operate in a much more realistic “world” than is often the case for such simulations, and produces a modeling environment that has the potential to give results that can be tested and applied in real world settings. In spite of the clear value of linking agent modeling platforms and GIS (Brown, et al. 2005) this potential has gone largely unrealized so far.

One of our top priorities is to complete linkage software between Java-based agent simulations such as DEVS-JAVA and GRASS GIS. This will allow us begin to couple the agent models of landuse decisions and practices with climate models (operationalized as raster maps in the GIS), spatially variable landscapes, and dynamic surface process models for landscape change. We can then begin the process of moving from workable model parameters to realistic ones, add multiple villages in different environmental contexts, and begin to add economic interactions between households and villages. Even more importantly, situating decision and landuse models on realistic landscapes will allow us to begin to evaluate alternative parameter suites through sensitivity analysis (multiple runs, periodically changing one parameter at a time to determine the nature and strengths of its effects). At this point we will have the beginnings of a fully functional laboratory of the past and we can begin the process of validation and tuning against the prehistoric record.

### SOFTWARE CONSIDERATIONS

A laboratory of the past for studying the long-term dynamics of Mediterranean socioecosystems, as we envision here, does not yet exist. Neither do many of the components needed to build such a laboratory. Nevertheless, we cannot hope to build such a complex modeling laboratory starting completely from scratch with the time and resources we have available. Hence, we are reusing and modifying existing software tools as much as possible to meet the requirements of the modeling laboratory. To this end, we generally find that high-end, open-source software is best suited to this larger endeavor. Open source software means that the original source code of a program is available to anyone—to examine and to modify to fit particular needs (whether or not the compiled version of a program is free or not). This is very important considering pioneering nature of this project. Using open source software means that we can build on the work of others in order to create a unique research environment for interdisciplinary archaeology—avoiding enormous development costs and time of starting from scratch—and then make that environment available to be used by yet others. Moreover, much of this open source software, developed largely by scientists and research professionals, and is of higher quality and computationally more sophisticated than commercial software.

Beyond these pragmatic reasons, there are several important philosophical considerations worth mentioning. The idea of building on the work of others, explicitly crediting their work, and disseminating widely a derivative work is a hallmark of western science and the main reason it has been so successful at giving us a much richer and useful understanding of our world. This is also the philosophy behind open source software. As information technology and computing becomes an increasingly critical and embedded part of science, it is troublesome to think that the computational component of a research program is a black box of proprietary software whose inner workings may be unknown to the scientists doing the work as well as to anyone else trying to understand it. Sometimes this is unavoidable, but increasingly there are equivalent or better alternatives whose algorithms can be freely examined. This is crucial to a modeling laboratory. It also fits closely with National Science Foundation requirements for making the results of research it funds as openly accessible to other researchers as possible.

Furthermore, much commercial software is largely available only in ‘first world’ nations. For reasons of cost, language, or simply marketing distribution, many scientists, land managers, planners, and policy makers in ‘second’ and ‘third world’ countries do not have access to commercial scientific software. Yet in many cases these are the very people who could most benefit from the tools developed in projects like ours. Using open source software, makes these tools globally available to be used where they are most needed. This also applies to students in a university setting, who often do not have the same degree of access to research software (nor the financial resources to purchase it) as faculty. While we still use proprietary software where appropriate (for example this paper is written using a commercial program) we are attempting to use open and accessible tools as much as possible in creating the modeling laboratory that is central to this research.

For much of our geospatial data management, analysis, and modeling, we are using GRASS GIS, image processing, and modeling software. GRASS has an especially rich array of modeling tools and analysis platforms that are especially well suited to archaeology. DEVS JAVA is also open source package, as will be software links we develop between GRASS and Java-based agent modeling platforms. We are developing a web-based GIS for access to project data and results in MapServer. Our data are currently being archived on a server running Linux, meaning we can give access to team members and collaborators beyond the ASU campus and the US borders without charging network seat license fees. These data will eventually be archived in the open source Fedora research data archiving system, managed by ASU libraries.

## CONCLUSIONS

A fundamental paradox of the human experience, recognized by writers, philosophers, historians, and social scientists, is that the overwhelming majority of the myriad of decisions that each of us make have little or no lasting impact on our lives—much less the lives of humanity more generally. But some do. Decisions such as agreeing to cooperate with neighbors to build and ditch that can bring water from the river to the fields can start a cascade of events that leads to cities, kings, wars, and scientific conferences...or it can lead to landscape degradation that makes an entire region unable to support a human population.

Archaeology directly confronts this paradox. We know that decisions are made by individuals, but cannot see them. The archaeological record, on the other hand, most often reveals the consequences of those decisions that had the most significant outcomes.

Over sixty years ago, Phillip Phillips (Phillips 1955) stated that “archaeology is anthropology or it is nothing”. While this dictum reminds archaeologists that foremost we are social scientists and that people are the object of our research, many archaeologists have also taken this to mean that our ideal goal is a cultural anthropology of the past. Such an ideal is simply incompatible with the nature of the archaeological record that comprises our data. However this should not relegate archaeologists to the role of “failed ethnographers, forever regretting the demise of the people they would like to talk to” (Shennen 2002: 9). Rather, we should recognize that we are best positioned among social scientists to address the paradox of why most human decisions and actions do little more than maintain the continuity of social reproduction and others are so significant that they can transform the world. Our view of the long human past gives us the unique opportunity to identify those decisions that had consequences that shaped the lives of future generations, and the contexts that enabled them to do so. This offers archaeology the chance to play a leading role in understanding human society and shaping our future. However, we cannot do this if we only seek to reconstruct the daily lives of past humanity. Reframing our research agenda to make the human past into laboratory for modeling the consequences of individual decisions offers a new opportunity to begin to realize this larger potential of archaeology. The Mediterranean Landscape Dynamics project is one of a handful of new research projects that are endeavoring to demonstrate the potential contribution of archaeology to the science of humanity. As a field centered on reconstructing the human past, archaeology, like all historical sciences, has followed Charles Lyell's uniformitarian observation that the present is the key to understanding the past. If we embrace a research agenda that emphasizes the past as a laboratory for social dynamics, it may turn out that the past is the key to our future.

## ACKNOWLEDGEMENTS

This project involves the efforts of many people beyond the authors. Although space does not permit a complete listing of all participants, we would like to mention a few of these researchers, in addition to those already cited in the text, who have contributed especially to the development of the modeling laboratory components described here. The paleoclimate modeling is being carried out by Jennifer Arzt and Reid Bryson, University of Wisconsin, Madison. Brett Hill, Hendrix College, is developing the regression functions to extend climate parameters across landscapes and Alexandra Miller, ASU, is implementing these in GRASS to create the climate maps. Also at ASU, Isaac Ullah, co-developed the GRASS scripts for modeling landscape dynamics. Sydney Rempel compiled ethnographic and epigraphic data used as a basis for landuse modeling. Erin Dimaggio is creating high-resolution DEMs from stereo aerial photographs for geologic mapping and Mariela Soto is creating vegetation maps. We also want to express our gratitude to our institutions who have supported the collaborative research that is key to the success of this project, and additional partner institutions of the University of Valencia, the University of Jordan, the University of Murcia, Geoarchaeological Research Associates, and the GRASS GIS Development Team.

## REFERENCES CITED

Allen, E., S. E. Falconer, C. M. Barton, H. S. Sarjoughian and P. L. Fall
2006 Modeling of agropastoral human activities using agent-based simulation. Paper presented at the 70th Annual Meeting of the Society for American Archaeology, San Juan, Puerto Rico.

Arzt, J.
n.d. *Modeled climatic variability in Mesopotania (10,000-3,000 BC)*. MS. on file in the Archaeoclimatology Laboratory, University of Wisconsin.

Barboni, D., S. P. Harrison, P. J. Bartlein, G. Jalut, M. New, I. C. Prentice, M.-F. Sanchez-Goñi, A. Spessa, B. Davis and A. C. Stevenson
2004 Relationships between plant traits and climate in the Mediterranean region: a pollen data analysis. *Journal of Vegetation Science* 15:635-646.

Barton, C. M., J. Bernabeu Auban, J. E. Aura Tortosa, O. Garcia and N. La Roca
2002 Dynamic landscapes, artifact taphonomy, and landuse modeling in the western Mediterranean. *Geoarchaeology* 17(2):155-190.

Barton, C. M., J. Bernabeu Auban, J. E. Aura Tortosa and O. Garcia Puchol
1999 Landscape dynamics and socioeconomic change: an example from the Polop Alto valley. *American Antiquity* 64(4):609-634.

Barton, C. M., J. Bernabeu Auban, O. Garcia Puchol, S. Schmich and L. Molina Balaguer
2004 Long-term socioecology and contingent landscapes. *Journal of Archaeological Method and Theory* 11(3):253-295.

Barton, C. M. and M. P. Neeley
1996 Phantom cultures of the Levantine Epipaleolithic. *Antiquity* 70(267):139-147.

Binford, L. R.
1981 Behavioral Archaeology and the "Pompeii Premise". *Journal of Anthropological Research* 37(3):195-208.

Brown, D. G., R. Riolo, D. T. Robinson, M. North and W. Rand
2005 Spatial process and data models: Toward integration of agent-based models and GIS. *Journal of Geographical Systems* 7:1-23.

Bryson, R. A. and R. U. Bryson

1997 High resolution simulations of regional Holocene climate: North Africa and the Near East. In *Third MIllennium BC Climate Change and Old World Collapse*, edited by H. Nüzhet Dalfes and G. Kukla, pp. 565-593. NATO ASI Series, Vol I 49. Springer Verlag, Berlin.

1999 Holocene climates of Anatolia: as simmulated with archaeoclimatic modeling. *Türkyie Bilimer Akademisi Arkeoloji Dergisi* 2:1-13.

Christiansen, J. and M. Altaweel

2004 Simulating a Bronze Age city state under stress. Paper presented at the Modeling Long-Term Culture Change, Santa Fe Institute, Santa Fe, NM.

Falconer, S. E.

2005 *A first generation model of agricultural landuse*. School of Human Evolution and Social Change, Arizona State University.

Haan, C. T., B. J. Barfield and J. C. Hayes

1994 *Design Hydrology and Sedimentology for Small Catchments*. Academic Press, New York.

Harowitz, A.

1979 *The Quaternary of Israel*. Academic Press, New York.

Hill, J. B.

2000 Decision making at the margins: settlement trends, temporal scale, and ecology in the Wadi al Hasa, west-central Jordan. *Journal of Anthropological Archaeology* 19:221-241.

2006 *Human Ecology in the Wadi al-Hasa: Land Use and Abandonment Through the Holocene*. University of Arizona Press, Tucson.

Kohler, T. A., G. J. Gummerman and R. G. Reynolds

2005 Simulating ancient societies. *Scientific American* 293(1):76-84.

Kohler, T. A. and D. Johnson

2004 Dynamic determinisstic resource-based models for Puebloan settlement. Paper presented at the Modeling Long-Term Culture Change, Santa Fe Institute, Santa Fe, NM.

Mayer, G. R., H. S. Sarjoughian, E. K. Allen, S. E. Falconer and C. M. Barton

2006 Simulation modeling for human community and agricultural landuse. In *Proceedings of the Agent-Directed Simulation Conference, Huntsville, Alabama*.

Mitasova, H. and L. Mitas

1993 Interpolation by regularized spline with tension. *Mathematical Geology* 25:641-669.

1999 Erosion/deposition modeling with USPED using GIS. University of Illinois at Urbana-Champaign.

2001a Modeling Physical Systems. In *Geographic Information Systems and Environmental Modeling*, edited by B. O. Parks, M. Crane and K. C. Clarke, pp. 189-210. Prentice Hall, New York.

2001b Multiscale soil erosion simulations for land use management. In *Landscape erosion and landscape evolution modeling*, edited by R. Harmon and W. Doe, pp. 321-347. Kluwer Academic/Plenum Publishers, New York.

Mitasova, H., L. Mitas, W. M. Brown and D. M. Johnston

1999 Terrain modeling and Soil Erosion Simulations for Fort Hood and Fort Polk test areas. Geographic Modeling and Systems Laboratory, University of Illinois at Urbana-Champaign.

Morrison, K. D.

2006 Failure and how to avoid it. Nature 440:752-754.

Phillips, P.

1955 American archaeology and general anthropological theory. *Southwestern Journal of Anthropology* 11:246-250.

Redman, C. L. and A. P. Kinzig

2003 Resilience of past landscapes: resilience theory, society, and the longue durée. *Conservation Ecology* 7(1):14 [online].

Ruter, A., J. Arzt, S. Vavrus, R. A. Bryson and J. E. Kutzbach

2004 Climate and environment of the subtropical and tropical Americas (NH) in the mid-Holocene: comparison of observations with climate model simulations. *Quaternary Science Reviews* 23(5-6):663.

Sarjoughian, H. S. and B. P. Zeigler

1998 DEVSJAVA: Basis for a DEVS-based Collaborative M&S Environment. Paper presented at the SCS Western Multi-Conference, San Diego, CA.

Spikins, P.

2000 GIS models of past vegetation: an example from northern England, 10,000-5000 BP. *Journal of Archaeological Science* 27:219-234.

Thaxton, C. S.
2004 *Grain size dependent transport phenomena on multiple scales.* PhD, North Carolina State University.

van der Leeuw, S. and C. L. Redman
2002 Placing archaeology at the center of socio-natural studies. *American Antiquity* 67(4):597-605.

Wandsnider, L.
1992 The spatial dimension of time. In *Space, Time, and Archaeological Landscapes*, edited by J. Rossignol and L. Wandsnider, pp. 257-282. Plenum, New York.

Wilkinson, T. J., M. Widel and e. al.
2004 Reconstructing a Third Millennium BC city state in upper Mesopotamia: the landscape framework for the simulation model. Paper presented at the Modeling Long-Term Culture Change, Santa Fe Institute, Santa Fe, NM.

Zaft, G.
2001 *Social Science Applications of Discrete Event Simulation: A DEVS Artificial Society.* Master Thesis, University of Arizona.

Zaft, G. and B. P. Zeigler
2002 Discrete Event Simulation of Social Sciences: The XeriScape Artificial Society. Paper presented at the World Multiconference on Systemics, Cybernetics and Informatics, Orlando, FL.

Zeigler, B. P., H. Praehofer and T. G. Kim
2000 *Theory of Modeling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems*. 2nd ed. Academic Press, San Diego.

Zvelebil, M., S. W. Green and M. B. Macklin
1992 Archaeological landscapes, lithic scatters, and human behavior. In *Space, Time, and Archaeological Landscapes*, edited by J. Rossignol and L. Wandsnider, pp. 193-226. Plenum, New York.

Table 1. Calculating simple landscape models.

| **Model** | **Equation** | **Parameters** |
|---|---|---|
| RUSLE | $E = R \times K \times LS \times C \times P$ | E = average soil loss,<br>R = rainfall intensity factor,<br>K = soil factor,<br>LS = topographic (length-slope) factor,<br>C = vegetation/landcover factor<br>P = prevention practices factor. |
| USPED | $ED = \mathrm{d}(T \times \cos a)/\mathrm{dx} + \mathrm{d}(T \times \sin a)/\mathrm{dy}$ | $ED$ = net erosion or deposition of sediment<br>$T$ (sediment transport) = RUSLE value<br>$a$ = topographic aspect |
| | | |

For more information on modeling protocols and parameters, see (Haan, et al. 1994) (Mitasova, et al. 1999).

Figure 1. Primary study areas for model building and testing.

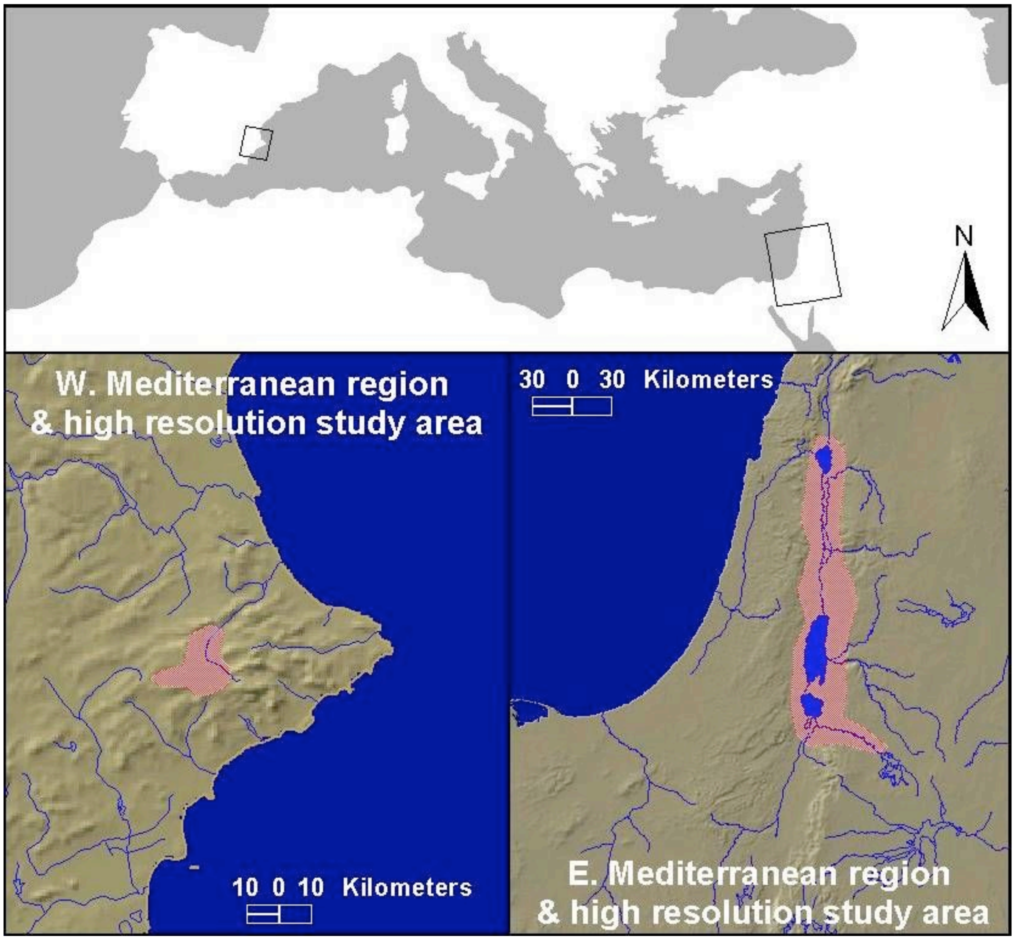


Figure 2. Modeling laboratory for studying interactions between landuse and landscapes.

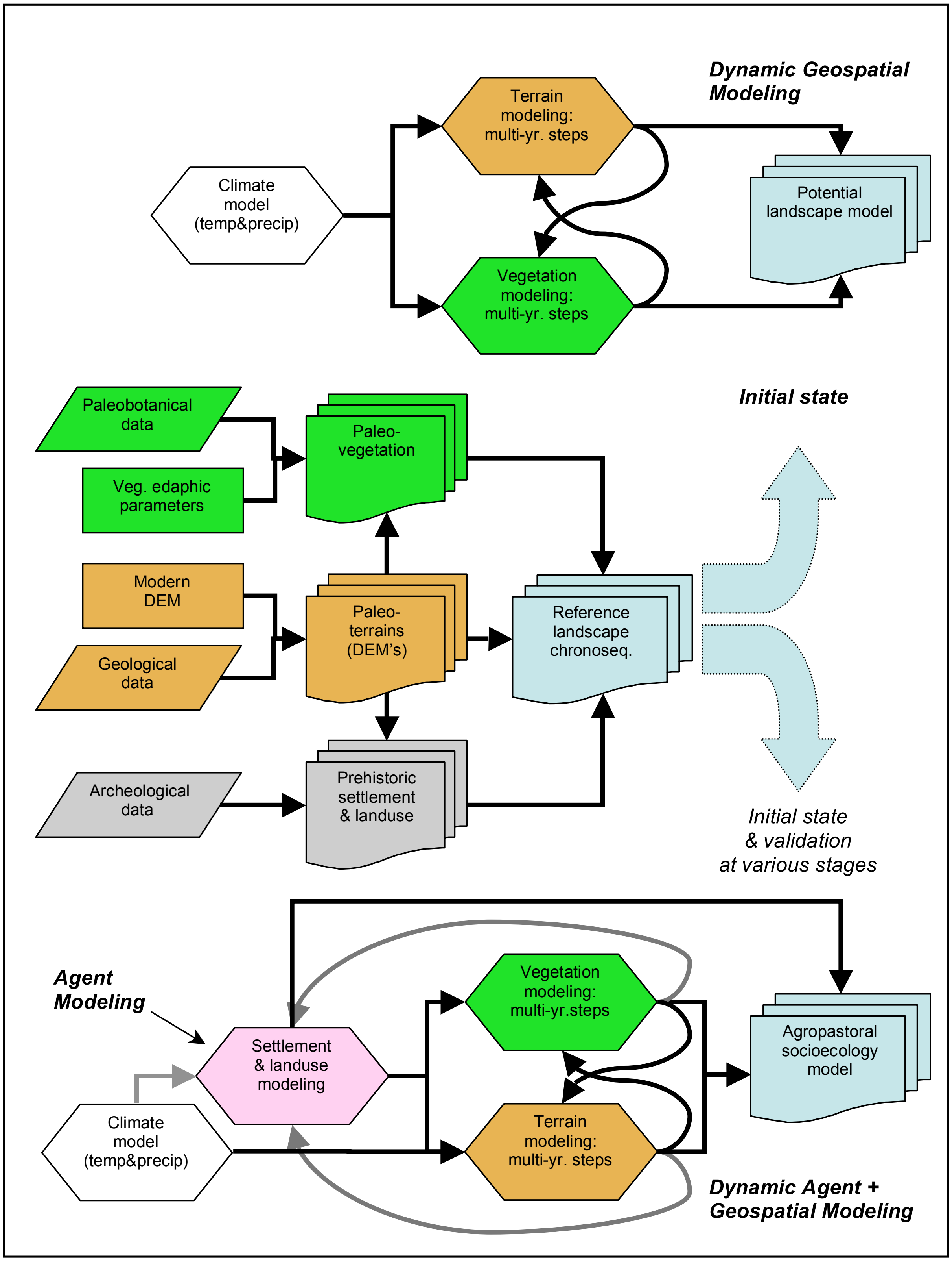


Figure 3. Examples of Terra ASTER topography. ASTER image of the Penaguila valley (decorrelation stretch of bands 1-3) and 30m ASTER DEM created from forward and backward camera in band 3.

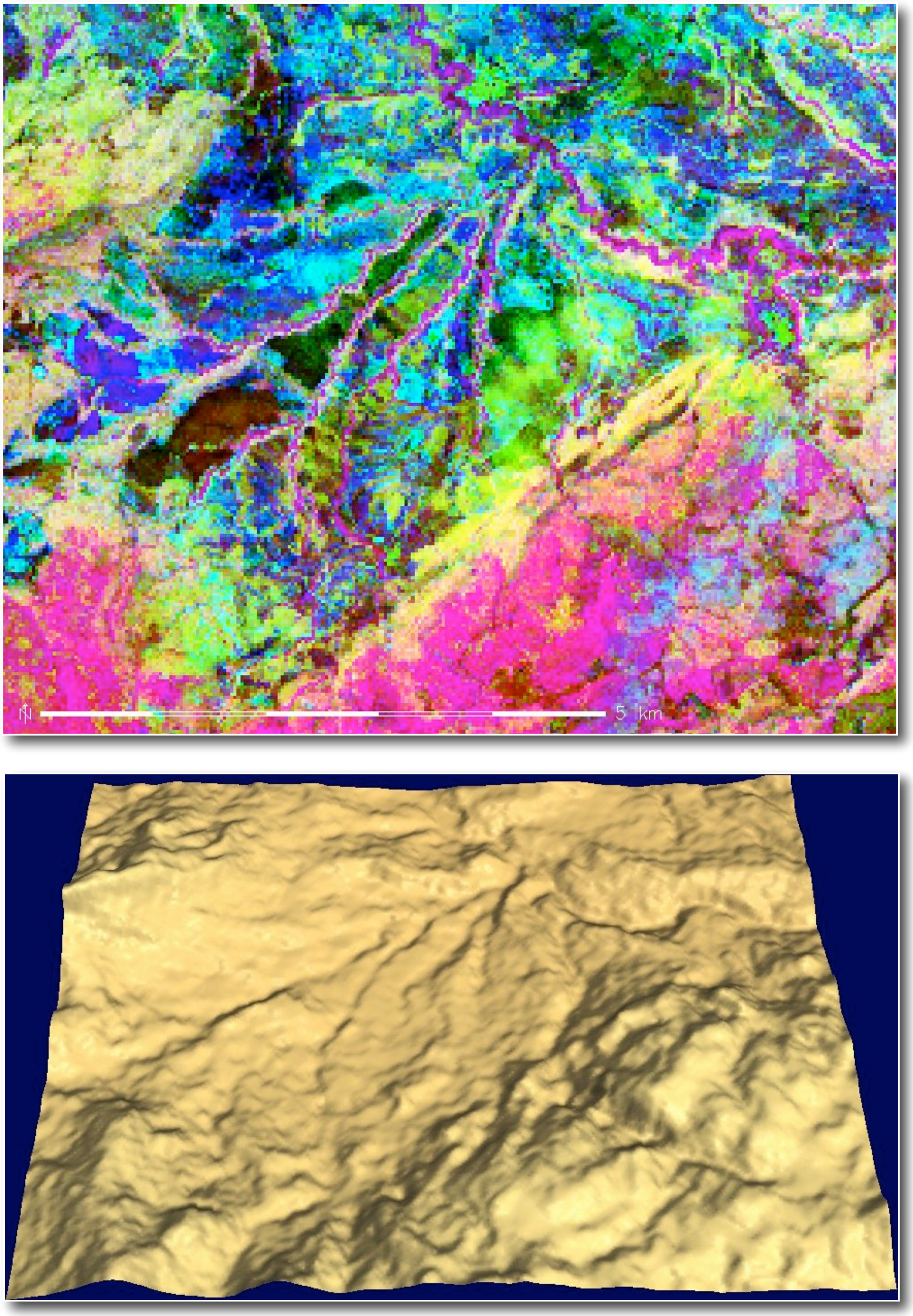
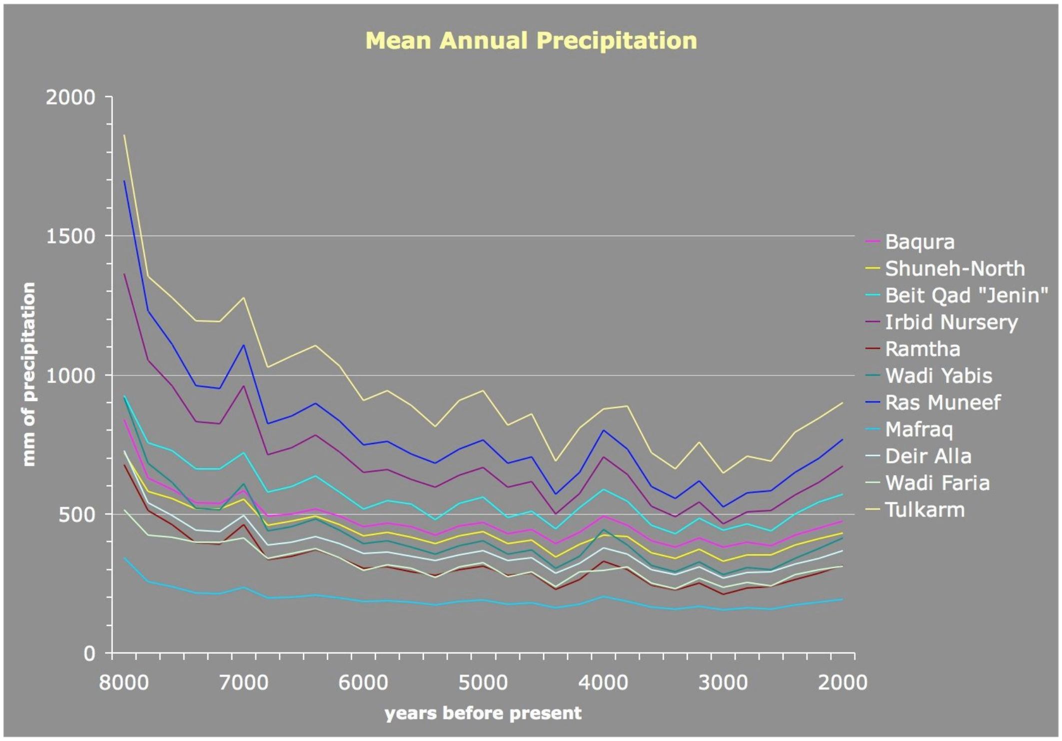


Figure 4. Examples of paleoclimate climate models for northern Jordan.



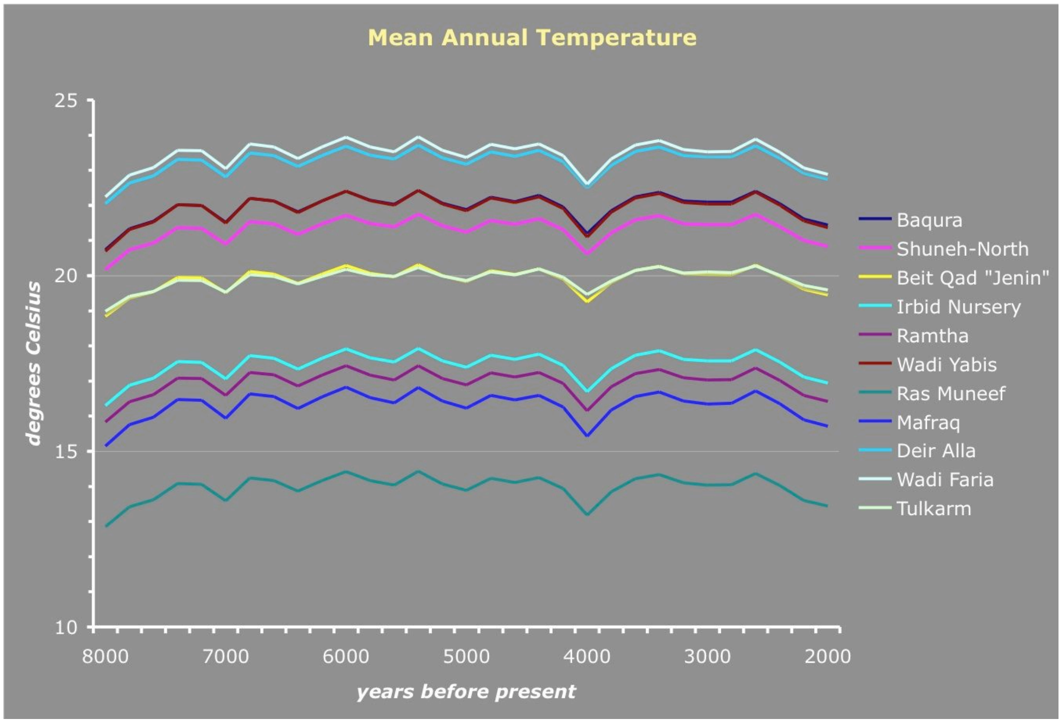


Figure 5. Spatially referenced maps of annual precipitation for northern Jordan in 8000 bp and 6000 bp.

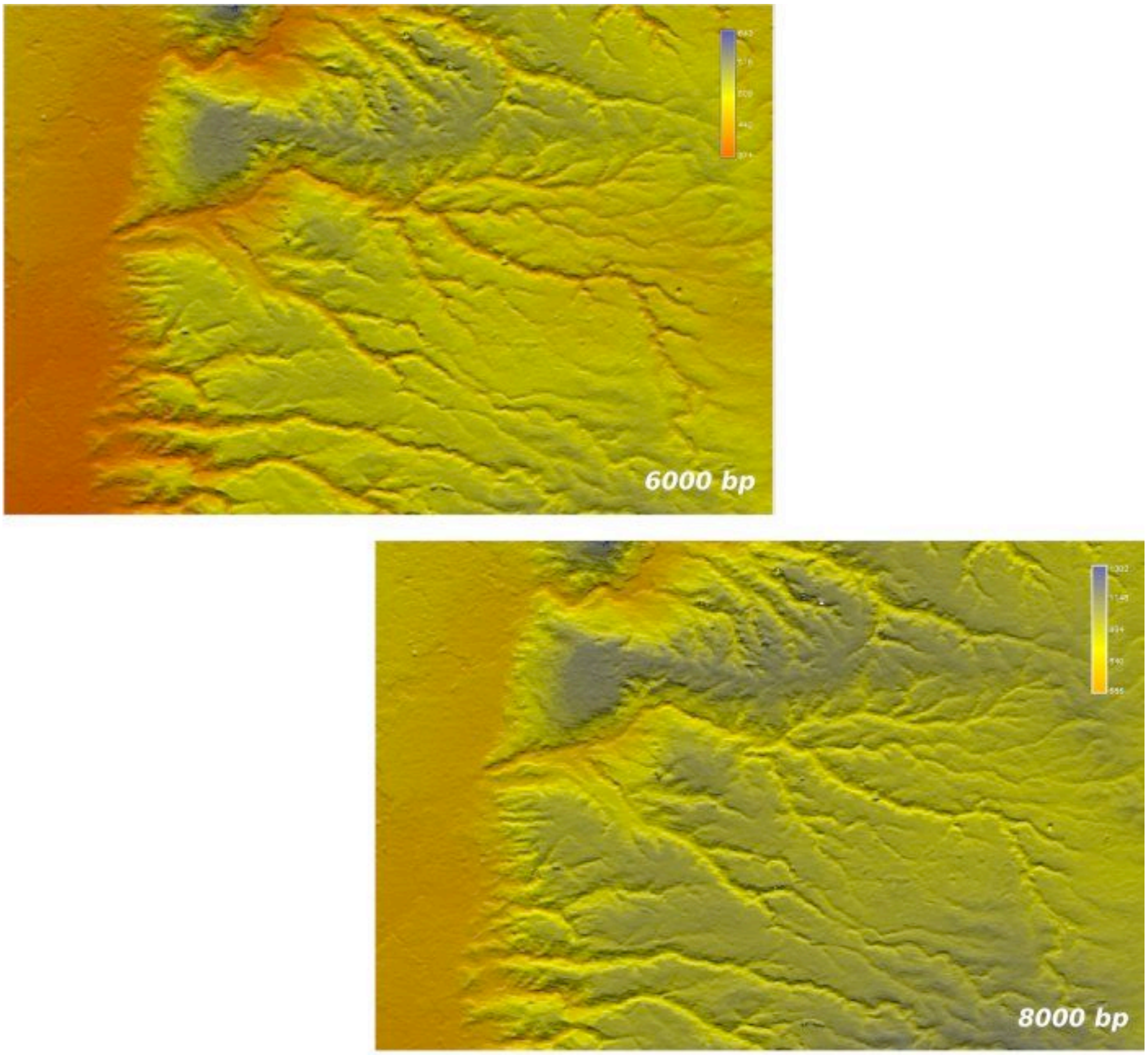


Figure 6. USPED erosion modeling in the Wadi Ziqlab, northern Jordan.

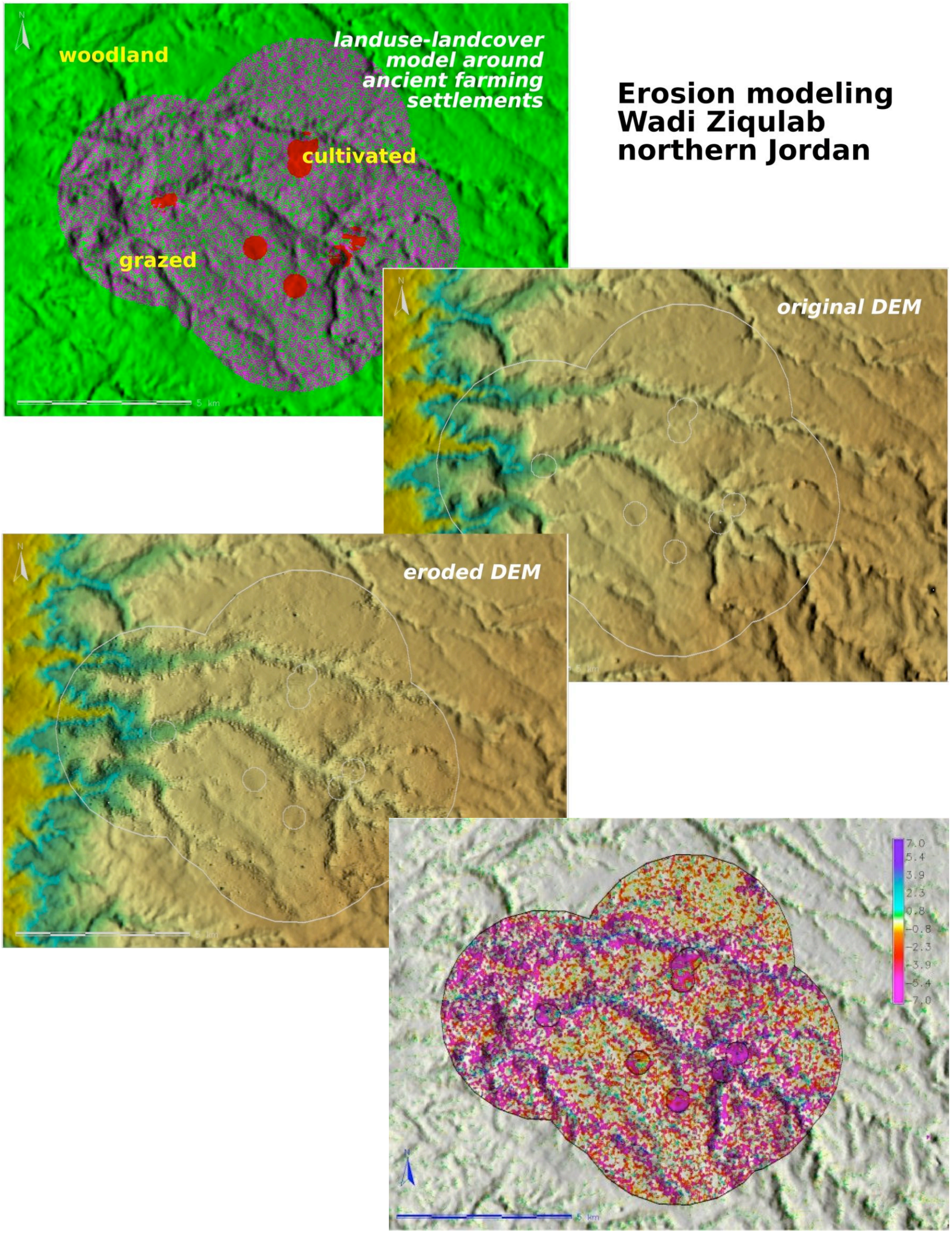
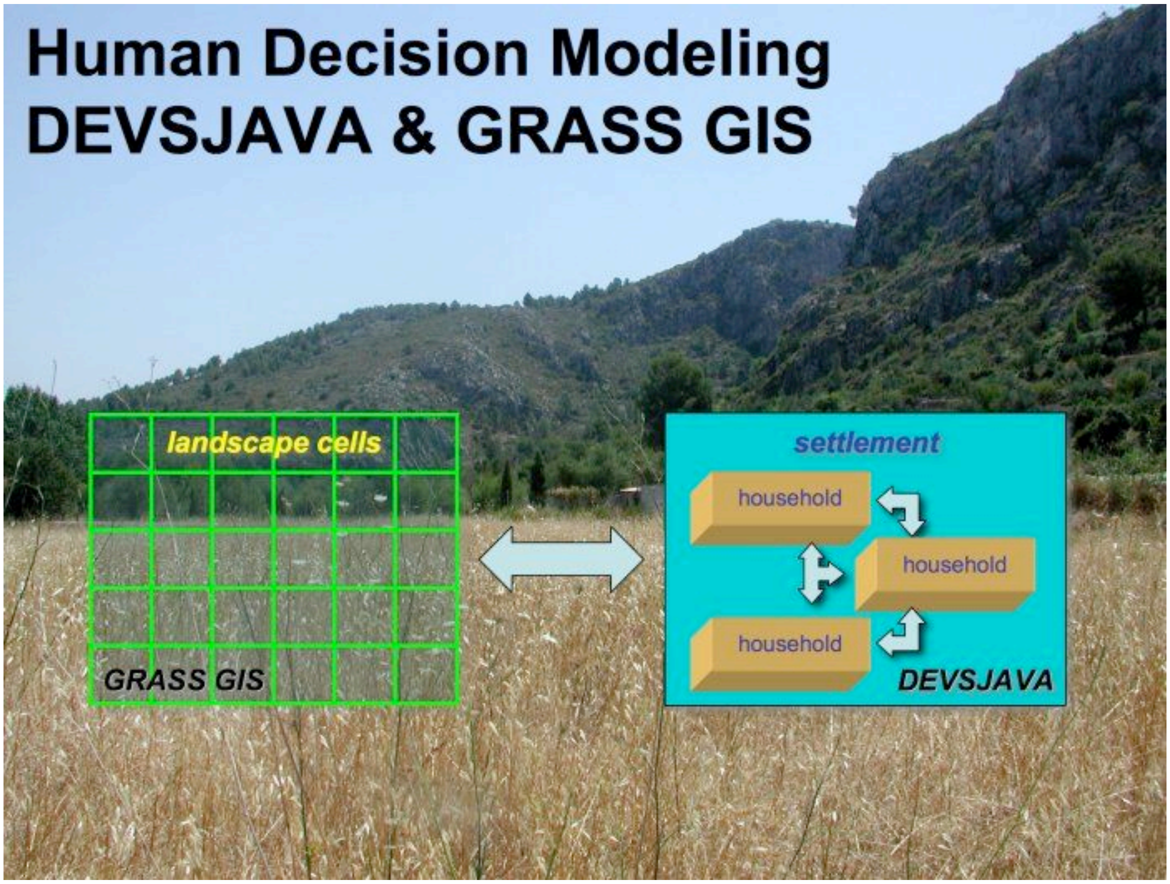


Figure 7. Schematic organization of agent-based simulation of human landuse (top). Prototype landuse model output showing population response to varying area available for cultivation (bottom).



Human Decision Modeling
DEVSJAVA & GRASS GIS