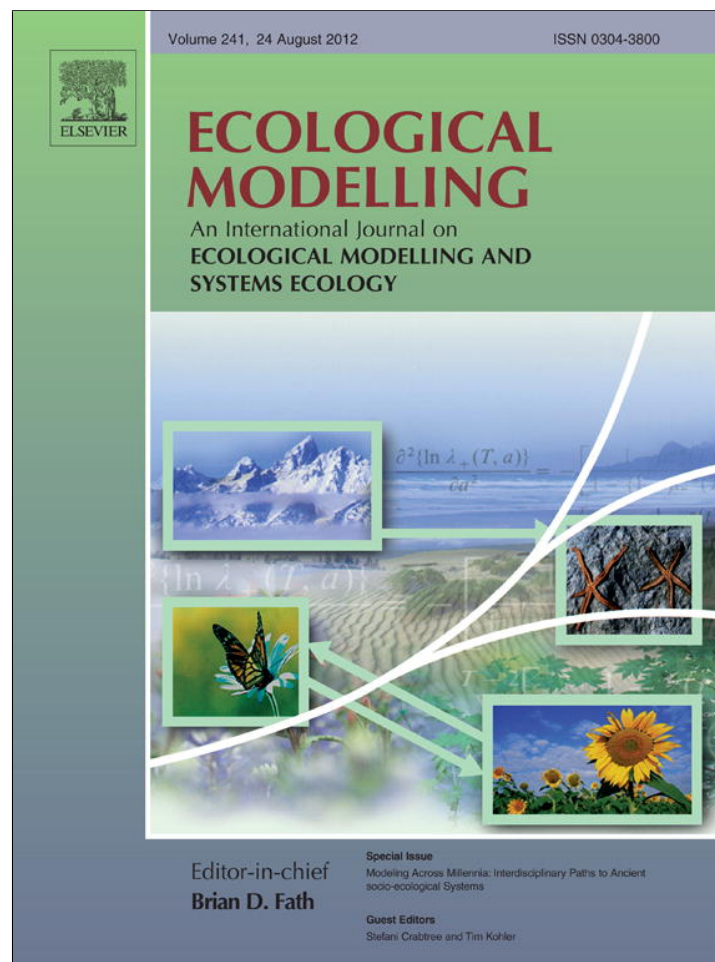


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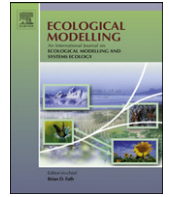
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# Ecological Modelling

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## Looking for the future in the past: Long-term change in socioecological systems

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### ABSTRACT

The archaeological record has been described as a key to the long-term consequences of human action that can help guide our decisions today. Yet the sparse and incomplete nature of this record often makes it impossible to inferentially reconstruct past societies in sufficient detail for them to serve as more than very general cautionary tales of coupled socio-ecological systems. However, when formal and computational modeling is used to experimentally simulate human socioecological dynamics, the empirical archaeological record can be used to validate and improve dynamic models of long term change. In this way, knowledge generated by archaeology can play a unique and valuable role in developing the tools to make more informed decisions that will shape our future. The Mediterranean Landscape Dynamics project offers an example of using the past to develop and test computational models of interactions between land-use and landscape evolution that ultimately may help guide decision-making.

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### 1. Introduction

From its inception as a formal field of study, the primary goal of archaeology has been the systematic, conceptual *reconstruction* of past societies. Most commonly, archaeological practice involves the creation of narratives that recount in history-like fashion, some aspect of past human lives and societies. In the latter half of the twentieth century, the goals of archaeology expanded to encompass explanations of how and why past people and societies acted and changed in the way they did – although there remains debate as to the relative importance of reconstruction (or *history*) and explanation, and what constitutes adequate explanation (Dunnell, 1982; Wylie, 1992, 2000; Barton and Clark, 1997; Hegmon, 2003; Killick, 2004; Pauketat and Alt, 2005). Even more recently, there have been calls for the insights from the historical sciences, including archaeology, to help inform social decision-making and better anticipate the long-term consequences of social action (van der Leeuw and Redman, 2002; Diamond, 2005; Turchin, 2008). These expanded aims of archaeology have the potential to shift the field from primarily descriptive accounts of the human past to a science of long-term social change with relevance to contemporary issues. However, archaeology faces significant problems in achieving these larger goals if archaeological practice remains based ultimately in

the reconstruction of past societies, due to the nature of the archaeological record.

#### 1.1. The missing record

The archaeological record comprises a very rich, diverse, and global dataset that derived from the successes and failures of numerous societies, and the interactions of societies with their environments (van der Leeuw and Redman, 2002; Diamond, 2005; Turchin, 2008). Archaeological data collection and analysis procedures have been particularly successful in interpreting this record to reconstruct manufacturing processes and uses for ancient material culture, physical aspects of resource processing and consumption, and the age and nature of particular events that contributed to the archaeological record – e.g., burials and caches, construction of buildings or monuments, or abandonment or destruction of communities (Wylie, 2000; Killick, 2004). However, when we attempt to extend interpretive reconstructions of the past beyond the production, physical use, and discard of material culture to those issues of individual and social beliefs, practices, interactions, and dynamics across space and time – the issues which most interest most archaeologists and the larger public – we encounter increasingly insurmountable problems with the archaeological record that cannot be mitigated by more sophisticated protocols for data collection (Hawkes, 1954).

Much of the dynamics of human society occur as interactions between social actors that leave no material traces. Anthropologists have long wrestled with the difficulties of interpreting the

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meanings of behaviors or even the sense of identity in societies with very different cultural knowledge and histories, even when they can observe and converse with living informants (Taylor, 1971; Geertz, 1973; Keesing, 1974; Abu-Lugbod, 1991). While many such prehistoric interactions are irretrievably lost, an important idea underlying modern archaeology is that the rich world of material culture (i.e., artifacts, built structures, and other material objects we make and use) can serve as a proxy for ethnographic observation of past societies (Longacre, 1964; but see Wobst, 1978). Indeed, material culture is deeply entwined with human social life and can even be an active agent of social reproduction (Newton, 1981; Hegmon, 1998; Pauketat and Alt, 2005).

Unfortunately, the social significance of much material culture is arbitrary, like language, and cannot be known without conversing with the users (Shennan, 2002; Killick, 2004). The spatial co-occurrence of material objects can sometimes provide clues to the social contexts in which they were embedded – e.g., many items used in a church have religious significance while most objects used together in a kitchen are related to food preparation and storage. However, the spatial associations of material culture when it was an active participant in human society usually are not preserved when it enters the archaeological record. Catastrophes like Pompeii and the prehistoric village at Ouzette, Washington, are thankfully rare. And while we might wish that occasionally aliens beamed up the members of a community, leaving all their material culture exactly where it was being used, the archaeological record is overwhelmingly produced by the discard of items as trash (Binford, 1981; Schiffer, 1987; Barton et al., 2002). Worse, most of the material record originally used in social practices has long since been lost to natural and cultural processes (Schiffer, 1987; Barton et al., 2002). Of that small part that remains, the great majority is undiscovered or inaccessible, or cannot be recovered due to time and money constraints. Those archaeological excavations that can be carried out often require a considerable amount of time and labor, but they represent a very tiny window into a mostly missing record. While we can gain reasonably secure knowledge about bits and pieces of events that took place at various times and places in the past, the narratives that fill in the enormous gaps in this knowledge to reconstruct the working of past societies are largely speculations – careful and statistically informed speculation in some cases, and imaginatively subjective in others. Archaeologists do a truly amazing job of recovering and analyzing the data available from the archaeological record, but it is impossible to reconstruct past societies by interpreting an archaeological record that cannot be recovered or that no longer exists. Attempting to do so places “... archaeologists in the role of ethnographers of a lost ‘ethnographic present’, struggling hopelessly to overcome the problems posed by the fact that the people they would like to talk to are long dead and most of the residues of their lives long decayed” (Shennan, 2002).

## 1.2. Computational modeling in archaeological research

If an ethnography of the past is beyond our reach, how then can we carry out scientific study of the long-term dynamics of human society and apply the resulting insights to better anticipate the future consequences of social action today? New digital technologies encompassing dynamic and space/time GIS, systems dynamics modeling, and multi-agent simulation – and coupling these and related technologies to enhance their capabilities (Sarjoughian, 2006) – offer the possibility of creating virtual worlds in which socio-ecological dynamics can be studied at temporal and spatial scales not possible in real-world contexts. Nevertheless, even the most sophisticated computer simulations cannot reconstruct the past any more accurately than do well-informed narratives. Like

these narratives, computational models can at best only reconstruct a selection out of a potentially infinite number of possible pasts.

However, such computational models can be treated as laboratory experiments in which alternative scenarios about the operation of complex socio-ecological systems can be studied and evaluated (Bankes et al., 2002; van der Leeuw, 2004; Kohler and van der Leeuw, 2007a). As experimental protocols, computational models can be parameterized on the basis of empirical observations and theoretical propositions about how the different components of a complex system interact. Parameters of interest can be varied systematically in these controlled, experimental environments, and the results compared to empirical data collected from real-world systems. This approach is particularly applicable in archaeology, where data consist almost entirely of the material outcomes of the operation of socio-ecological systems operating in different contexts over different time spans. That is, rather than attempt to intuit the complex operation of past human societies on the basis of fragmentary, static data, archaeologists can use their diverse record as a testbed for evaluating the output of multiple experimental runs that represent alternative models of social dynamics. This protocol can help to build a better understanding of how societies past and present operate (i.e., explain social processes), and can more directly contribute to better social decision-making by helping to create more robust models of socio-ecological systems. While many archaeologists have long recognized the value of hypothesis testing, generating hypotheses and quantitative test implications about complex socio-ecological systems in a systematic and transparent way rapidly becomes impractical in narrative or even linear equation form when more than a few interacting variables are involved. Such complex, multivariate interactions can be expressed and studied explicitly, however, when translated into computational models and treated as controlled experiments (Kohler and van der Leeuw, 2007a). Moreover, conducting such experiments in a digital environment makes it possible to explore social dynamics among many interacting actors and at temporal scales that would be impossible to carry out with real human groups.

For a model-based approach to archaeology to be successful, archaeologists will need to be able to articulate social theory in explicit, algorithmic form and partner closely with scientists collecting empirical information about modern human societies (e.g., cultural anthropologists, cultural geographers, sociologists, and political scientists) and relevant biophysical systems (e.g., geomorphologists, hydrologists, soil scientists, ecologists, and climatologists). While the computational thinking needed to express processes as algorithms (Wing, 2006) is still foreign to most archaeologists, interdisciplinary collaboration with other social and natural scientists is a well-established tradition within archaeology (Butzer, 1982; e.g., Dincauze, 2000; McIntosh et al., 2000; Smith, 2011). To illustrate potential for computational modeling to help archaeology better achieve current aims of explaining social dynamics and informing social decision-making, we review recent work in the Mediterranean Landscape Dynamics Project (MedLand), an interdisciplinary research endeavor, funded by the National Science Foundation Biocomplexity program, to develop a computational modeling laboratory for studying the recursive interactions of agropastoral land-use and landscape evolution.

## 2. The Mediterranean Landscape Dynamics Project (MedLand)

### 2.1. Overview

The MedLand modeling laboratory was created to carry out virtual experiments on the long-term, recursive interactions between society, land-use, and environmental change. We selected intensive



Fig. 1. Location of the two intensive study areas of the Mediterranean landscape Dynamics project.

study areas in eastern Spain and western Jordan for building (Fig. 1) the modeling laboratory, because they represent the range of social and ecological contexts spanning the ancient and modern Mediterranean. However, many other terrestrial regions also could be studied in the MedLanD laboratory. Because of the diversity of processes involved in complex socio-ecological systems, the MedLanD laboratory is a modular, hybrid environment that tightly couples different modeling approaches (Mayer et al., 2006; Mayer and Sarjoughian, 2009) (Fig. 2). Landscape evolution and related biophysical processes are modeled using a cellular automata approach in a raster GIS-environment; human land-use and related decision-making can be modeled stochastically in the GIS or through agent-based simulation (ABM); regression-based models of past climate and maximum entropy models of vegetation communities (Soto-Berelov, 2011) provide values for initialization and, in the case of climate, parameters input during model runs to simulate environmental change over time. The interactions among heterogeneous models are managed through a Knowledge Interchange Broker (KIB) model that handles data exchanges, timing, and model coordination (Sarjoughian, 2006). We briefly review these components here, with additional details published elsewhere (Ullah and

Bergin, 2012; Barton et al., 2010a,b; Ullah, 2011; Mitsova et al., 2012).

2.1.1. Modeling land-use practices

When agropastoral land-use is modeled stochastically, farming and grazing patches are randomly distributed within catchments around communities, delineated in a GIS using Python-based scripts that combine values for walking energy required to reach landscape cells, suitability for farming and/or herding (including slope, vegetation, and soil depth and fertility), and the amount of land needed to sustain the population of the community. Depending on the kinds of land-use to be modeled, catchments for intensive and shifting cultivation (also called Swidden cultivation) and for animal herding can be calculated in this way (Fig. 3). During each model cycle, cells in which agropastoral land-use takes place are selected from within each catchment. For intensive cultivation, all cells are selected to represent farm plots that are repeatedly cultivated using practices like manuring or crop-rotation to maintain fertility. For shifting cultivation only a fraction of the catchment cells are cultivated in any given cycle; these are randomly allocated each cycle to simulate the reuse of some plots and the abandonment

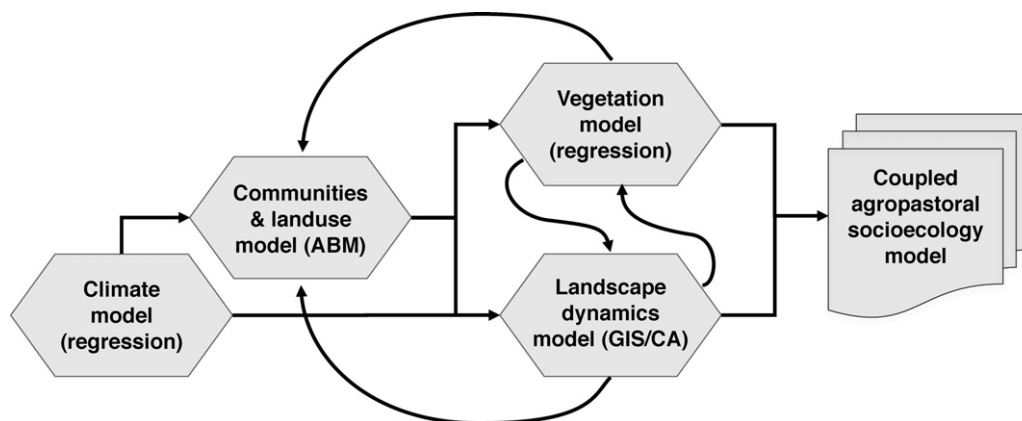
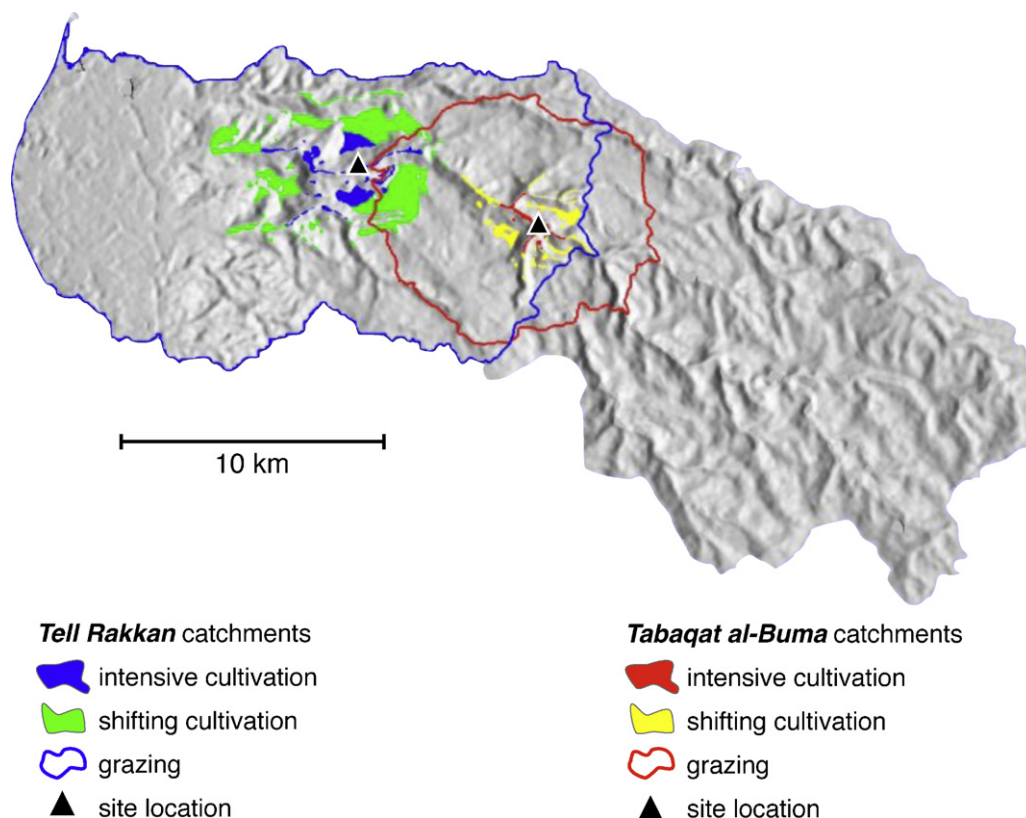


Fig. 2. Schematic of MedLanD modeling laboratory components.



**Fig. 3.** Farming and grazing catchments calculated for two Neolithic communities in the Wadi Ziqlab valley of northern Jordan. Tell Rakkan was a small village dated to the PPNB; Tabaqat al-Buma was a Late Neolithic hamlet (see Banning, 1996). Farming catchments for intensive cultivation and five-year fallow cycle shifting cultivation are shown for each community, along with a grazing catchment that assumes a 33% annual use.

of others, along with new landscape patches cleared for cultivation. In the example discussed below, 20% of the total farming catchment was cultivated in any cycle to simulate a five-year fallow cycle. Stochastic modeling of animal herding is similar to shifting cultivation. In the first example below, we modeled grazing intensity such that a third of the grazing catchment around each community was utilized in any given cycle.

Alternatively, the MedLand laboratory can model farming households as individual agents, organized into villages. Agents employ decision rules to choose land cells to farm or graze on the basis of their farming returns (calories that affect birth and death rate) and needs (based on household size), the potential productivity of land for agropastoral use (including soil depth and fertility, slope, and current vegetation), and costs to use the land (including access on foot) (Ullah and Bergin, 2012; Mayer et al., 2006; Mayer and Sarjoughian, 2009; Barton et al., 2010a). As opposed to stochastic modeling of land-use, where cultivated and grazed cells are allocated randomly within catchments whose sizes are estimated on the basis of subsistence needs and fallow/grazing cycles, each household agent chooses the best available landscape patches in a round-robin whose order is randomized each execution cycle of the model so that no household will have first access to better lands than other households. Agents also choose land cells from which to collect fuel-wood, based on household size, availability of woody vegetation, and energy costs to access a cell on foot.

For both stochastic and agent-based modeling approaches, land-use directly affects landscapes by altering vegetation cover. Cultivation removes any land-cover on a cell and replaces it with cereal grasses. Grazing and wood gathering reduces plant biomass on a cell by an amount calculated on the basis of grazing intensity (number of animals per patch) and household size (Fig. 4) (Fleuret and Fleuret, 1978; Carles, 1983; Fox, 1984; Lubbering et al., 1991;

Tabuti et al., 2003; Bhatt and Sachan, 2004; Karanth et al., 2006; Naughton-Treves et al., 2007; Ullah, 2011). Vegetation regrows at a rate calculated from empirical studies of abandoned Mediterranean fields (Ruecker et al., 1998; Bonet and Pausas, 2004, 2007). While cultivation always transforms a cell's land-cover to cereals, grazing and wood gathering can have impacts that vary from severe to none, depending on the rates of biomass reduction and vegetation regrowth in each cell. In the agent-based land-use model, soil fertility also declines each time a plot is cultivated, following an empirically determined function (Ruecker et al., 1998; Knops and Tilman, 2000; Mele et al., 2003; Potter, 2006). Soil fertility and soil depth (affected by erosion and deposition) in a landscape patch, along with rainfall have empirically calibrated impacts on cereal yields (Carter et al., 1985; Christensen and McElyea, 1988; Araus et al., 1997, 1998; Slafer et al., 1999; Sadras and Calvino, 2001; Barzegar et al., 2002; Quiroga et al., 2006; Pswarayi et al., 2008). Plant biomass likewise can affect animal yields (ovicaprines in the cases that we've modeled to date) if it declines too much (Carles, 1983; Lubbering et al., 1991; Nablusi et al., 1993; Gulelat, 2002; Degen, 2007; Ullah, 2011).

### 2.1.2. Modeling landscape change

Whether modeled stochastically or as agent behavior, anthropogenic changes to land-cover impact the location and intensity of erosion and deposition. Land-cover is one of the parameters of the surface dynamics model, scaled as C-factor used in the well-known Revised Universal Soil Loss Equation (RUSLE). Other inputs include raster DEMs of surface and bedrock topography, soil erodability (scaled as K-factor for RUSLE), and rainfall intensity (calculated from the annual rainfall total and annual number of rainfall days). The landscape evolution model is implemented as a Python-based script in the GIS-environment that calculates the net erosion or

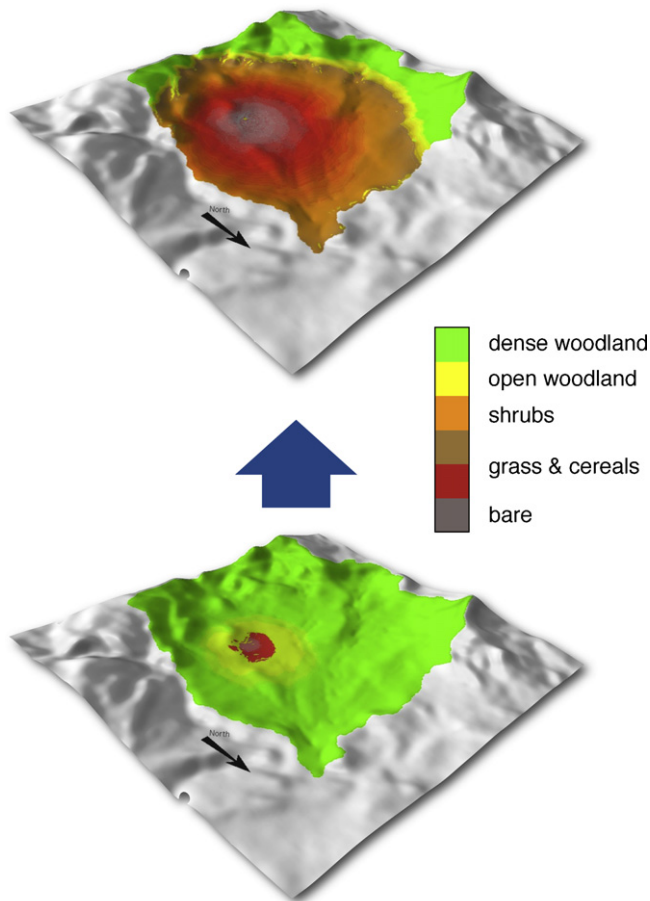


Fig. 4. Modeled vegetation change around village in the Río Penaguila valley, Spain over 100 years.

deposition in each cell of a raster map of the landscape. Different process equations better represent sediment flux in different topographic contexts. We use a diffusion equation for the areas near drainage divides, a transport-limited equation (a 3D version of the Unit Stream Power Erosion–Deposition equation) for hillslopes and gully heads, and an equation based on the reach-average shear stress for channels (Mitasova et al., 2012). The spatial points of transition between the different equations are calculated on the basis of the upslope area contributing runoff to each cell and the topographic profile curvature, values readily obtained using GIS tools (Fig. 5).

Net erosion/deposition rates are converted to elevation change values (negative for erosion and positive for deposition), and added back to each cell of a raster digital elevation model (DEM) such that the landscape is lowered or raised accordingly. This process is iterated for each cycle of the model – with input land-cover from human activities, vegetation regrowth, and rainfall values – to simulate ongoing landscape change from decades to millennia. The landscape evolution component of the modeling laboratory alters soil depth and slope, affecting the potential productivity of landscape cells (Fig. 6). For ABM-simulated land-use, this also changes the attractiveness of cells for farming or grazing in the subsequent modeling cycle. Hence, human activities directly and indirectly affect landscapes, and landscape evolution recursively affects human land-use decisions, creating complex interactions between the human and non-human components of these socio-ecological systems.

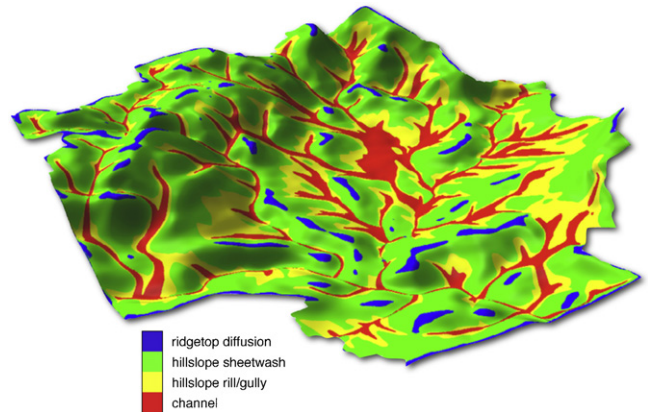


Fig. 5. Regions of the Río Penaguila Valley where different sediment transport processes operate, and where we used different algorithms to model surface process dynamics.

### 2.1.3. MedLand software and current development

The MedLand modeling laboratory is built entirely with open-source software that is widely available, customizable, and whose internal algorithms are public. GRASS GIS <<http://grass.osgeo.org>> (Neteler and Mitasova, 2008) is used for landscape evolution and stochastic land-use modeling; Java-based DEVS-Suite model libraries and simulator <<http://devs-suitesim.sf.net>> (Kim et al., 2009) are used for agent-based modeling of household land-use and model coupling; and NASA's World Wind Java libraries <<http://worldwind.arc.nasa.gov>> (Maxwell et al., 2009) provide a visualization engine that contextualizes the model in real-world landscapes. Use of these platforms has optimized the modeling software for high efficiency and speed on inexpensive commercial workstations, and across all current standard desktop operating systems. Currently, the landscape evolution model will complete an annual modeling cycle on a landscape of 1,000,000 cells in well under one minute. Stochastic land-use modeling adds a few seconds to this time. When coupled with the Java ABM, modeling cycles are still well under three minutes and we have recently completed updates that should reduce run-times significantly. This means that modeling runs simulating centuries or millennia are feasible on easily accessible hardware. We are also testing the potential for this modeling environment to be ported to a high-performance computing environment where multi-run parameter sweeps can be accomplished in reasonable time spans.

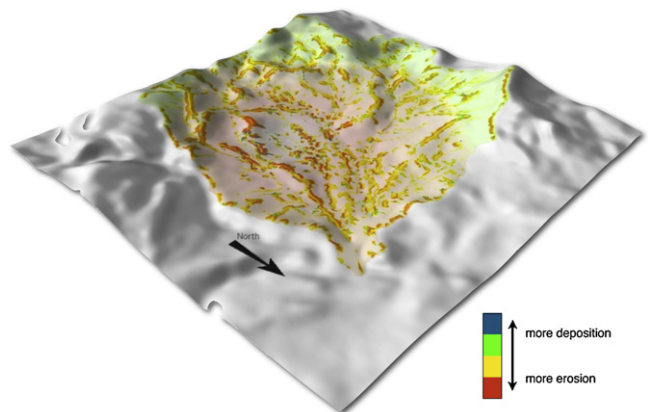


Fig. 6. Net erosion and deposition in the Río Penaguila valley, Spain after 100 years. Vegetation model from Fig. 4 superimposed as a semi-transparent overlay to show relationships between land-use and landscape dynamics.

2.2. Examples of results

We have begun using the MedLanD modeling laboratory to carry out experiments on consequences of land-use practices by small-scale subsistence agropastoral communities on landscapes of Jordan and Spain, at opposite ends of the Mediterranean basin (Fig. 1). We summarize three of these below.

2.2.1. Varying land-use and community size in landscapes of northern Jordan

One suite of experiments was performed using stochastic land-use modeling coupled with the landscape evolution model described above (Barton et al., 2010a,b). In these experiments, we examined the effects of varying cultivation from intensive cultivation of the same small area around a community to shifting cultivation with a five-year fallow cycle, adding ovicaprine grazing to subsistence practices, and varying the size of the farming community over different time spans (Table 1). We parameterized the modeling laboratory with values derived from Neolithic farming communities of northern Jordan (Banning, 1995, 1996, 2003) and examined the consequences of varying land-use over the course of two and ten generations, 40 and 200 years respectively. To calibrate our results, however, we also modeled landscape evolution in the same region, under the same climatic conditions but without human agropastoral activities. This kind of ‘contrafactual’ prehistory allowed us to compare the net impacts of changing the nature and extent of agropastoral practices in ways not possible with more normal practice of inferring past societies from the real archaeological record.

Many of the experiments conformed to expectations about the impacts of different land-use practices, lending confidence to the overall performance of the modeling algorithms. For example, shifting cultivation over the course of two generations (40 years) results in greater soil loss than repeated cultivation of a few plots (e.g., with manuring); farming with associated ovicaprine grazing produces more erosion than farming without grazing; larger communities with more people farming and grazing more land will have a greater impact on the landscape than smaller communities (Fig. 7). On the other hand, some of the most interesting model outcomes were less intuitive because of the complex interactions between land-use and landscape dynamics, including an apparent phase-change in the socio-ecological system as communities grow past a threshold size that is probably uniquely determined by local environmental conditions. This effect is most apparent when land-use practices involve shifting subsistence (i.e., not for market) cultivation and ovicaprine grazing. This combination is common even today in many parts of the world, and displayed the greatest potential for landscape impacts overall in the modeling experiments. As noted above, the combination of shifting cultivation and grazing resulted in some amount of erosion and deposition in all cases. But for small hamlets, the amount of soil loss can be substantially offset by soil accumulation, as sediments eroded from one part of the agropastoral catchment are redeposited in another area (Fig. 8). Erosion tends to take place in areas where it has little impact on agropastoral productivity, whereas accumulation occurs in high productivity areas. Under these conditions, the economic impacts of mixed agropastoral land-use can be negligible or even beneficial. However, if communities pass a locally determined threshold size, the consequences of identical land-use practices change such that soil loss greatly exceeds soil accumulation within a land-use catchment, and soil loss occurs more in high-productivity areas giving it greater economic impact. This imbalance is clearly evident after two generations and continues over the long-term (i.e., for 200 years), with the potential for leaving a catchment unsuitable for farming.

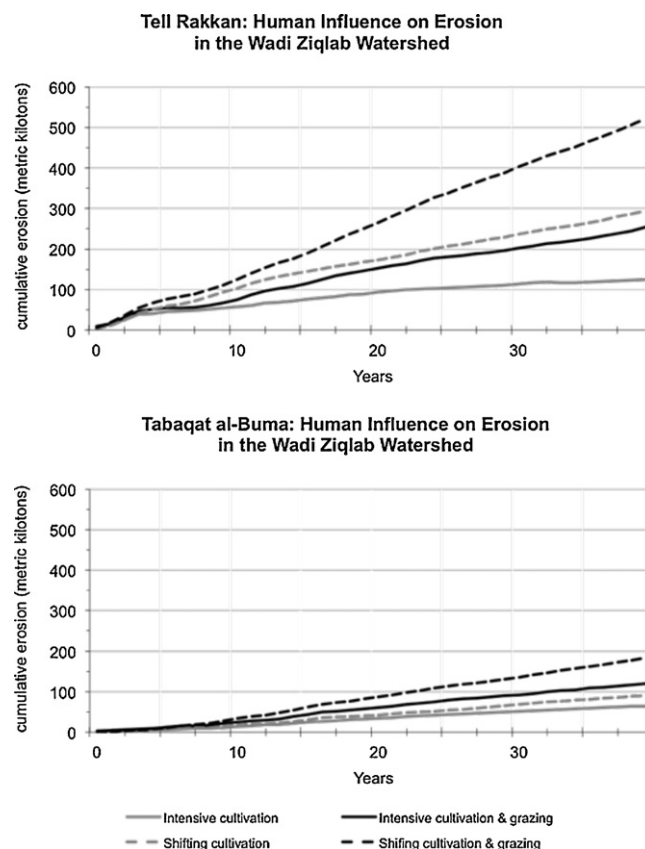


Fig. 7. Modeled cumulative erosion for different land-use patterns after 40 years in catchments around different size communities in the Wadi Ziqlab (see Fig. 3).

One strategy to mitigate such environmental degradation is, not surprisingly, to reduce community size through emigration or fissioning. Another less obvious solution discovered in these experiments is to increase the area devoted to grazing relative to cultivation, moving zones of soil loss into uncultivated uplands and providing more sediment for redeposition in the areas around farmed fields. Conservation measures, like terracing, also could be instituted but may require some degree of increased cooperation ensure the availability of sufficient labor for terrace construction and long-term maintenance. This kind of investment in landesque capital and intensification of land-use has often been accompanied by the growth of inequalities in social power and

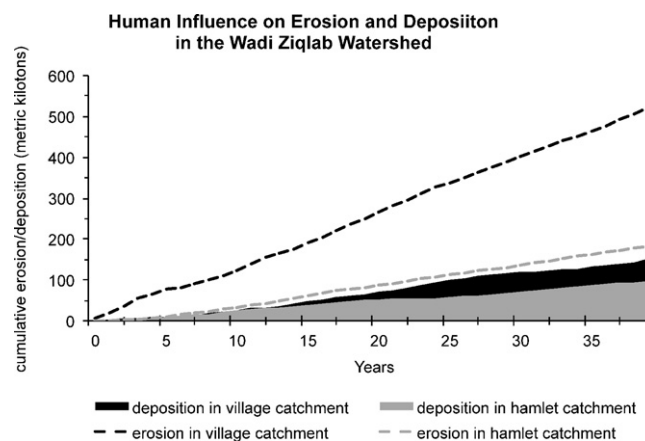


Fig. 8. Comparing modeled cumulative erosion and deposition for shifting cultivation and grazing after 40 years in catchments around different size communities in the Wadi Ziqlab (see Fig. 3).

**Table 1**  
Different suites of modeling experiments carried out for agropastoral communities set in the landscape of the Wadi Ziqlab, northern Jordan. Heavy line outlines experiments discussed in the text.

Settlement	Precip. and soil	Agropastoral land-use experiments	
Small village with 5-20 families; similar to Tell Rakkan ca. 8400 cal BP (PPNB)	918.5 mm/yr <i>R</i> -factor = 6.69 <i>K</i> -factor = 0.42	No cultivation	No grazing
		Intensive cultivation	No grazing
		Intensive cultivation	Grazing
		Shifting cultivation	No grazing
Hamlet with 1-5 families; similar to Tabaqat al-Bûmaca. 7400 cal BP (PN)	783.7 mm/yr <i>R</i> -factor = 5.26 <i>K</i> -factor = 0.42	No cultivation	No grazing
		Intensive cultivation	No grazing
		Intensive cultivation	Grazing
		Shifting cultivation	No grazing
			Grazing

prestige. The results of these modeling experiments broadly correspond with empirical evidence from the archaeological record (Rollefson and Kohler-Rollefson, 1992; Legge and Harris, 1996; Martin, 1999; Kuijt and Goring-Morris, 2002; Quintero et al., 2004; Simmons, 2007; Twiss, 2007; Rosen, 2008). The earliest farming societies of northern Jordan and surrounding areas of southwest Asia have been divided chronologically by archaeologists into the Pre-Pottery Neolithic A (11,500–9500 cal BP), Pre-Pottery Neolithic B (9500–7900 cal BP), Pre-Pottery Neolithic C (7900–7500 cal BP), and Late Neolithic (7500–7000 cal BP) (Banning, 2007; Simmons, 2007). During the PPNA, most communities were very small, and paleobotanical and faunal remains indicate that subsistence strategies focused on cereal cultivation without ovicaprine herding. Mixed farming and herding strategies appeared during the subsequent PPNB (Zeder, 2008). Also, many PPNB and PPNC communities were much larger than those of the PPNA, and some may have housed over a thousand inhabitants. Beginning in the late PPNC and continuing through the Late Neolithic, however, most of these larger settlements were abandoned or greatly reduced in size, with most of the regional population again living in very small communities. Additionally, plant and animal remains suggest that some groups may have begun to rely more on animal herding, marking the beginning of mobile pastoral economies. Finally, the late Neolithic record of certain parts of the larger region is interpreted to suggest increased social inequality along with investments in landesque capital.

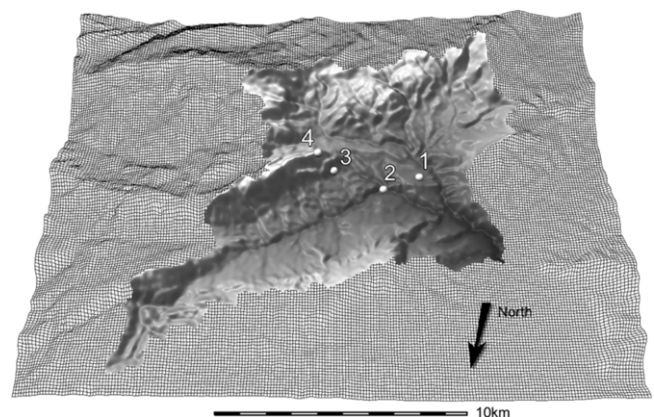
2.2.2. Varying community location in landscapes of eastern Spain

A second set of experiments carried out in the MedLanD modeling laboratory studied the consequences of situating a small farming village in different topographic contexts within the Río Penaguila and upper Río Serpis Valleys of eastern Spain, the location of one of the earliest known farming communities in the Iberian Peninsula (Bernabeu Auban et al., 2003; Bernabeu Aubán and Orozco Köhler, 2005). In this case, land-use practices were modeled in an ABM context, in which each household agent chose and used land according to a set of decision rules, and its evaluation of its subsistence needs and the characteristics of the surrounding landscape (Ullah and Bergin, 2012). In four different suites of experimental runs (Fig. 9), a simulated village was located on an alluvial plain (for easy access to land for farming and grazing), in a canyon bottom (for seclusion), at the base of a cliff (for defensibility), and on a ridgetop (to visually control the surrounding territory). In each locale, all initializing parameters besides geographic setting were kept the same for the village. The agents farmed and grazed the land around each site for 100 years and data were collected on population size, economy, vegetation cover, and erosion/deposition (Fig. 10).

When the village was located on the alluvial plain it was initially more successful than when placed in the other settings, as

measured in terms of population growth and agricultural returns. However, this success also led to a recursive, self-amplifying growth cycle of increasing population, expanding cultivation and grazing, and soil degradation and loss. When situated in the other locales, the village grew more slowly, experienced more variable economic returns, and had a smaller and more stable population with slightly less detrimental impacts on the surrounding landscape. The most surprising results came from the ridge-top location. Intuitively, a village located in such a topographic setting, surrounded by steep slopes at high risk of erosion, should suffer considerable land degradation and soil loss. However, it suffered only slightly more erosion other locales (2.6% more than alluvial plain site) and had less impact on surrounding vegetation (Fig. 11). Using the same decision-making algorithms employed when the village was in other topographic settings, the agent inhabitants of the ridge-top village grazed their flocks on the slopes adjacent to the community and cultivated fields at the base of the ridge. Without nearby cultivation, grazing was evenly distributed on the slopes, limiting erosion. Moreover, the erosion that did occur, accumulated at the base of the slopes, enriching the areas cultivated. Associated with this, there was less degraded vegetation in the area surrounding the ridge-top locale than for the other settings.

While archaeological sites are commonly found in a variety of topographic settings, including ones analogous to those used for this experiment, we do not know of any study to assess the ecological impact of prehistoric settlements in such different settings. This set of experiments, then, does not reconstruct any particular past society. Rather, it provides a set of hypotheses about the long-term ecological consequences of socially mediated site placement that can be tested against the archaeological record.



**Fig. 9.** Different topographic localities for an agropastoral community in the Río Penaguila. (1) On level terrain, (2) in barranco, (3) at the foot of a steep slope, and (4) on a ridgetop.



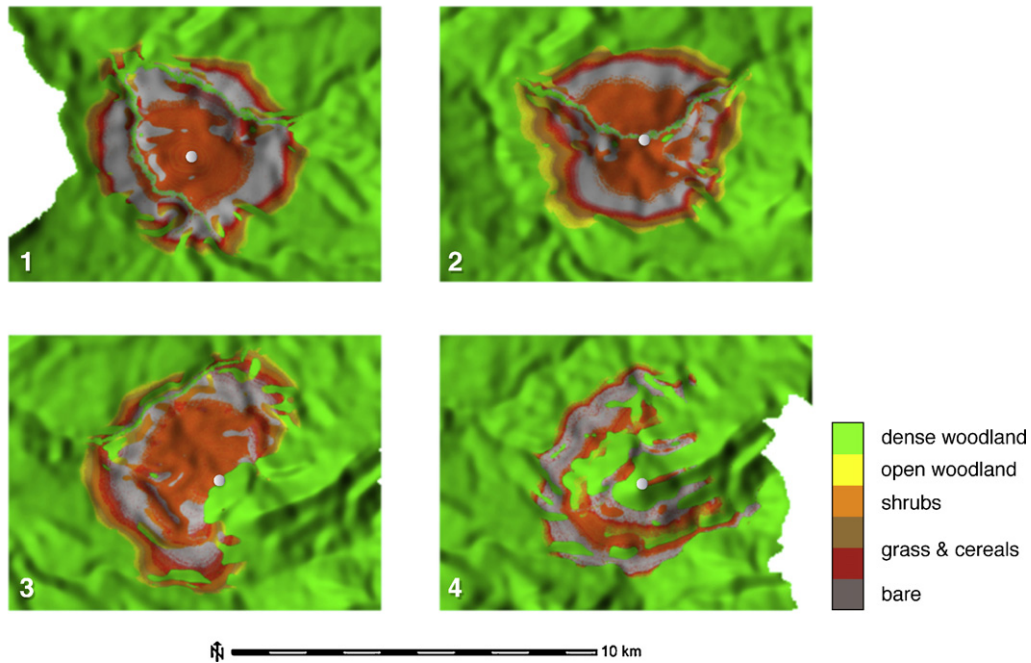


Fig. 10. Modeled vegetation around a community placed in different topographic settings (see Fig. 9) after 100 years.

2.2.3. Processes that created the modern landscape

A final example reports the initial results of a series of experiments now underway to better understand how the interaction of land-use and climate transformed ancient landscapes into those we see today. The modern landscape is a product of thousands of years of complex human–environment interaction, and thus is very different than the landscape first populated by Neolithic peoples. However, vestiges of these ancient landscapes still remain, and can be identified through careful geomorphological field work. By sampling the modern topographic data from those portions of the

landscape that have been relatively unchanged since the Neolithic, we can use GIS tools to interpolate a “paleoDEM” of the Neolithic landscape that models ancient topography in those areas that have changed in the intervening years. We have created such a paleoDEM for the Rio Penaguila watershed of eastern Spain.

Although this paleoDEM is only a model of what the ancient topography might have been like, it provides a starting point for simulation experiments to investigate landscape formation processes. We have situated one or more Neolithic settlements on this paleoDEM, using archaeological data about Neolithic communities

Land-cover After 100 Years for 4 Locations

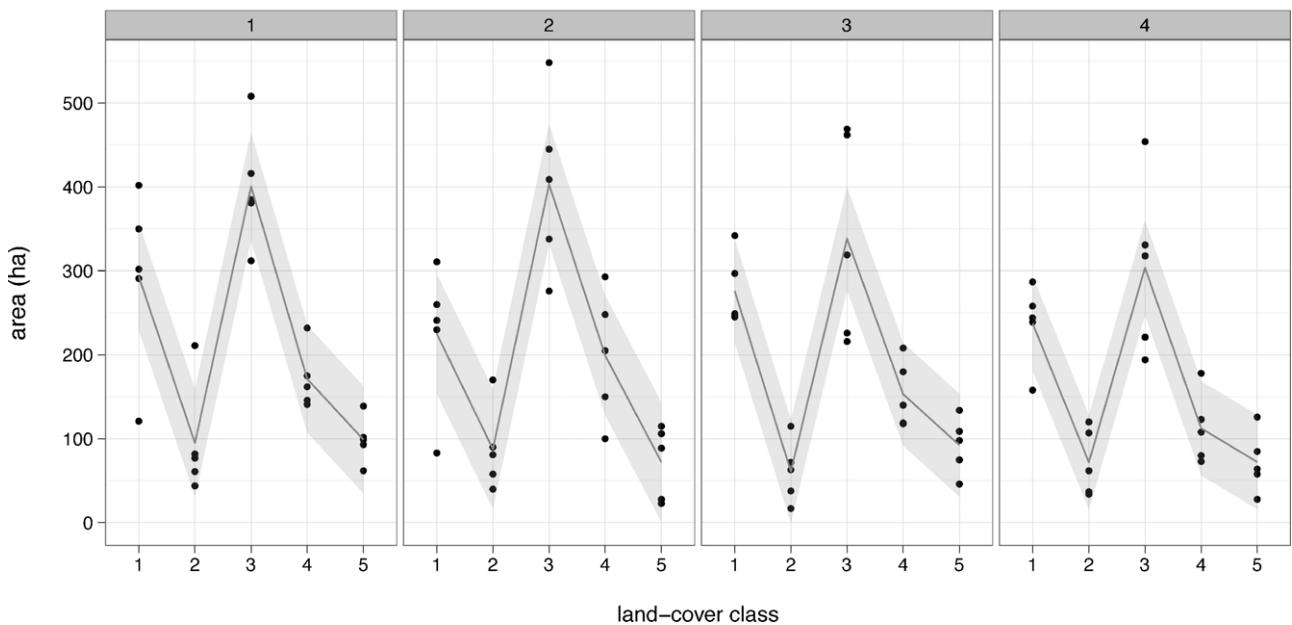
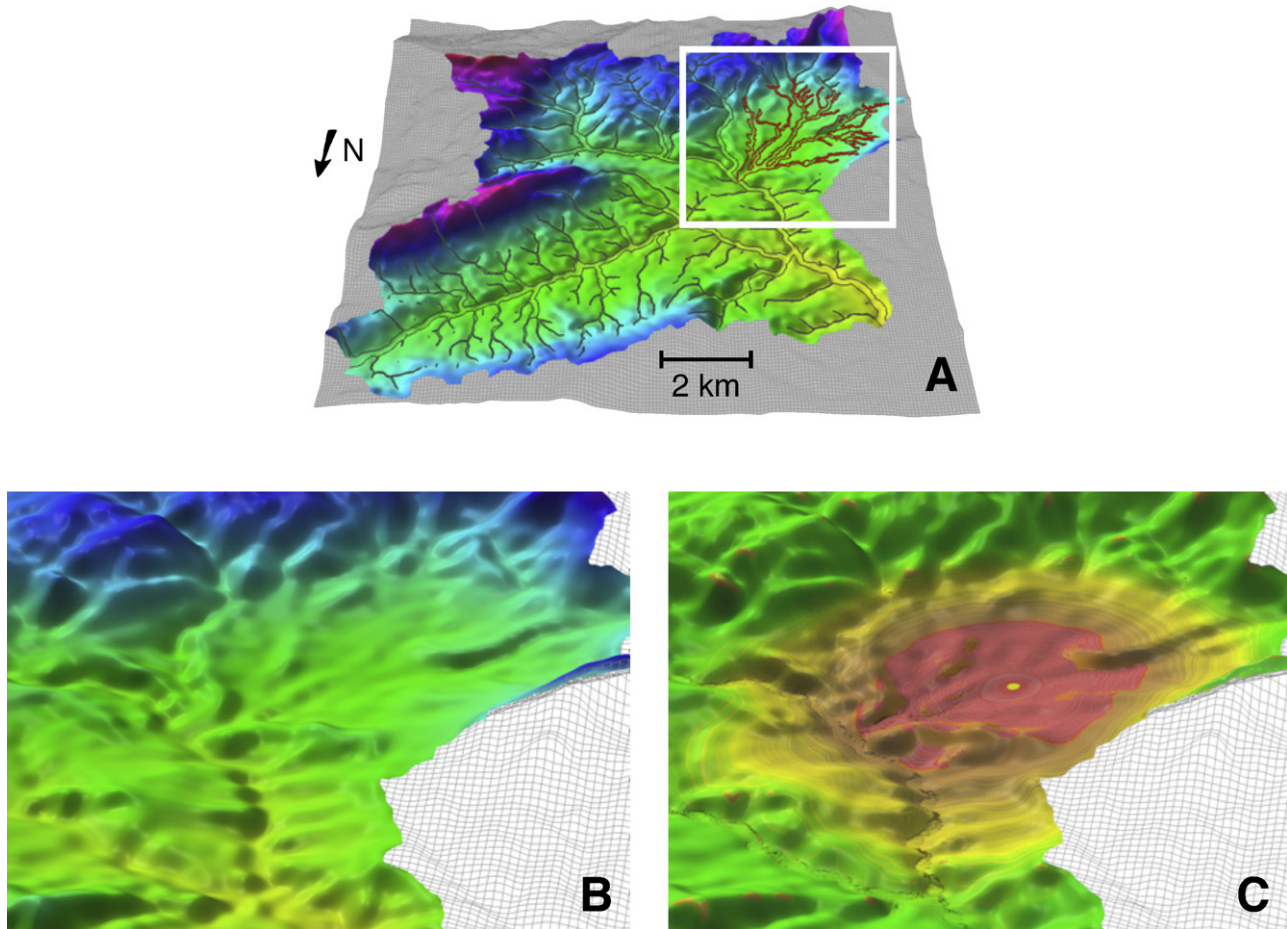


Fig. 11. Area occupied by different vegetation classes after 100 years of modeled farming and herding for a community placed in different topographic settings (see Fig. 9). Vegetation classes: 1 = bare to sparse herbs, 2 = herbs/grasses, 3 = shrubs, 4 = incipient woodland, 5 = maturing woodland. Line connects mean of 5 runs for each locality with shading showing 95% confidence interval.



**Fig. 12.** Paleodem and terrain after 500 years of modeled farming and herding in the Rio Penaguila watershed. (A) Modern DEM with post-Neolithic terrain outlined in black and red. White rectangle indicates area detailed in B and C. (B) Detail of paleodem with modeled terrain in outlined areas in A. (C) Detail of paleodem after 500 years of modeled agropastoral land-use. Note incising *barrancos*. Color in C indicates land-cover: central yellow dot is Neolithic hamlet, surrounding reddish zone are areas of cultivated and fallowed fields, brown and yellow zones are grazed areas in shrubland and degraded (or rejuvenating) woodland, green is undisturbed Mediterranean woodland.

in the Penaguila (Bernabeu Auban et al., 2003, 2006) and a wide array of ethnographic information about subsistence farming to parameterize the land-use aspect of the model. This is coupled with modeled climate data to allow for systematically testing the consequences of land-use and climate change (e.g., Miller et al., 2009a,b). We illustrate preliminary results in Figs. 12 and 13.

The Penaguila Valley is characterized by a series of ancient terraces into which deep *barrancos* have been incised in prehistory but after the earliest Neolithic (Barton et al., 2002). The archaeological record of this region indicates significant changes between the early and late Neolithic (Neolithic I–IIa, ca. 5600–3700 cal BC, and Neolithic IIb–c, ca. 3700–2300 cal BC) in settlement location and size, domesticates emphasized, and social complexity and differentiation (Bernabeu Auban et al., 2006; McClure et al., 2009; Miller et al., 2009a,b). Paleoclimatic models also suggest coterminous shifts in the distribution of precipitation, prompting suggestions that some combination of social change, land-use change, and climate change initiated geomorphic processes that produced the modern landscape (McClure et al., 2009; Miller et al., 2009a,b).

#### 2.2.4. Our new experiments are designed to test these ideas

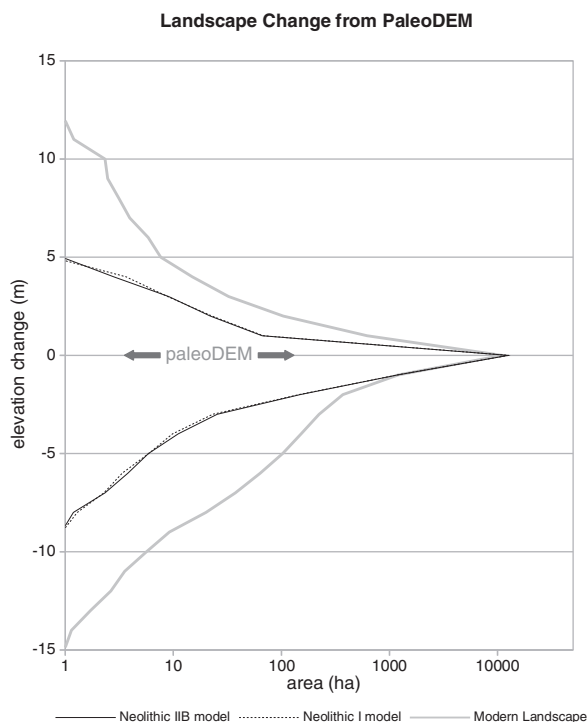
Fig. 12 shows the modern landscape (A), along with a detail of the paleodem (B) and modeled terrain after 500 years in the same location (C). This land-use/landscape model displayed in (C) was run with a rainfall pattern characteristic of the Neolithic IIb. The incising *barrancos*, that characterize the modern landscape, can be

seen clearly within the major and some minor drainages. Fig. 13 compares the result of land-use/landscape modeling with Neolithic I and Neolithic IIb rainfall patterns to the modern landscape. The modern landscape and both Neolithic models are represented as divergence from the paleodem.

Both Neolithic I and IIb models show landscapes that are shifting toward the modern terrain pattern, although neither model has converged on the modern landscape after 500 years of land-use. Importantly, almost identical results are produced under both Neolithic I and Neolithic IIb climatic conditions. We emphasize that these are very preliminary results, and we have not yet completed the kind of multiple runs and sensitivity tests needed to confirm them. However, if they hold up in further experimental work, it appears that climate change of the magnitude estimated for the Neolithic is not of itself a primary driver of modern landscape formation in this region. In further experiments we will systematically examine the impacts of different human land-use practices.

### 3. Discussion

The MedLand modeling laboratory is designed to improve our understanding of the causes and consequences of long-term change in Mediterranean socio-ecological systems, not to create 'digital reconstructions' of the past. It uses the archaeological record as a means of testing and refining models of the complex interactions between societies and the natural environment, rather than a basis



**Fig. 13.** Histogram comparing of amount of landscape change from paleoDEM to modeled Neolithic landscapes and modern landscape. Y-axis is erosion or deposition in meters above or below the surface of the paleoDEM; X-axis represents the area in hectares experiencing each value of erosion or deposition (note log scale).

for inference. This kind of modeling can provide a clearer picture of the kinds of dynamics that could have created the archaeological record. However, an equally if not more valuable use of such models is to provide better information about the likely outcomes of decisions we are making today. While there is a growing recognition of the potential for archaeological insights to help us to make better informed decisions about our future, the primary contributions from archaeology have been in the form of cautionary tales distilled from narrative reconstructions of the past (Redman, 1999; Diamond, 2005). However, it is often difficult to find sufficient parallels between the issues of modern urban societies and those in archaeological narratives of the distant past to actually apply those insights to decision-making in any concrete way. Moreover, there remains considerable disagreement about which inferential reconstruction actually represents the 'true' past, and hence the applicability of any insights to be gained from each reconstruction (Lawler, 2010).

Embedding quantitative and computational modeling into the regular practice of archaeology can help to reframe it from a field seeking the past to one more focused on the long-term dynamics of human society. The archaeological record can also be transformed from a simply a source of inspiration for creating stories about the past to a means for testing and refining models of human society. Although the record is too sparse and fragmentary to serve as a basis for reliable inference about the operations of past societies in many cases, it is a rich and diverse testbed for the evaluation of formal models. Such an approach offers a way for archaeological practice and knowledge to contribute in more diverse and substantial ways to a broader understanding of socio-ecological systems and, because of a focus on social dynamics rather than societies of the past, to better anticipating the future consequences of today's decisions.

Expanding the goals of modern archaeology in this way, poses formidable challenges. Not only is there no general agreement

across the discipline that this is a desirable course to take, there has yet to be any serious discussion of this approach. While some have suggested that a model-based archaeology could serve as a unifying middle ground in current debates over whether archaeology should endeavor to be more of a social science or within the humanities, this remains to be seen (Kohler and van der Leeuw, 2007a). Moreover, there is a serious lack of awareness of modeling approaches among archaeologists, and an equal lack of the skills needed to build and use models; this problem is not limited to archaeology but pervades the social sciences (Alessa et al., 2006).

Nevertheless, there is a small, but growing number of archaeologists (and other social scientists) who recognize the potential value of applying new modeling approaches to long-term change in complex human systems (e.g., Kohler and van der Leeuw, 2007b; Barton et al., 2010b). This is particularly important because modeling is not just the use of computer programs, but also requires in-depth knowledge about the nature of systems being modeled and the conceptual frameworks that have been used to study them. Computer scientists can help archaeologists develop models, but archaeologists also need to develop modeling skills to be able to use relevant technologies effectively. One way to leverage the impact of the small body of early adopters of modeling approaches and technologies is to self-organize into 'communities of practice' in which knowledge about these methods can be more easily disseminated and shared, outside normal channels of academic communication. Formal and computational models are particularly amenable to dissemination through online libraries and repositories, but present a number of pragmatic difficulties for dissemination via normal publication channels (Alessa et al., 2006). This kind of self-organization is taking place in other fields that find such models valuable for studying complex natural processes – for example, the Community Surface Process Modeling System <<http://csdms.colorado.edu>> for models of terrestrial and marine systems of earth's surface (Voinov et al., 2010). Recently, a similar network for knowledge exchange about modeling in the socio-ecological sciences was established (the Network for Computational Modeling in the Socio-ecological Sciences <<http://www.openabm.org>>), with an online library, discussion forums, and educational materials (Janssen et al., 2008). Archaeologists with expertise – or an interest – in applying these modeling approaches to questions of social process and change can improve their skills and benefit their colleagues by participating in community organizations like these. This kind of intellectual bootstrapping is needed in order for archaeological faculty to have sufficient expertise and awareness of these new technologies to train the next generation of professionals. Archaeology need not abandon its intellectual roots in exploring the human past, but the greatest promise for its future lies in applying new conceptual and methodological tools in research on the long-term dynamics of human society.

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