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Phil. Trans. R. Soc. A 2010 **368**, 5275-5297

doi: [10.1098/rsta.2010.0193](https://doi.org/10.1098/rsta.2010.0193)

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Land use, water and Mediterranean landscapes: modelling long-term dynamics of complex socio-ecological systems

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The evolution of Mediterranean landscapes during the Holocene has been increasingly governed by the complex interactions of water and human land use. Different land-use practices change the amount of water flowing across the surface and infiltrating the soil, and change water's ability to move surface sediments. Conversely, water amplifies the impacts of human land use and extends the ecological footprint of human activities far beyond the borders of towns and fields. Advances in computational modelling offer new tools to study the complex feedbacks between land use, land cover, topography and surface water. The Mediterranean Landscape Dynamics project (MedLand) is building a modelling laboratory where experiments can be carried out on the long-term impacts of agropastoral land use, and whose results can be tested against the archaeological record. These computational experiments are providing new insights into the socio-ecological consequences of human decisions at varying temporal and spatial scales.

Keywords: land use; landscape; agriculture; archaeology; Neolithic; southwest Asia

1. Introduction

Unquestionably, water plays a critical role in all human societies, past and present. The most obvious social concerns about water centre on ensuring the 'right' amount of this critical resource in the right places and at the right times to maintain human health and life; both too little and too much water can be problematic. Desertification is a looming issue for many parts of the world and threatened past societies in arid regions. An overabundance of water can be equally detrimental, including floods, hurricanes and tsunamis. Many of the most harmful impacts of forecast climate changes facing humanity in the coming century revolve around changes in the distribution of water in relation to human settlement and activities—from increased risk of inundation for coastal cities to the expansion of deserts into agricultural lands. While these water-related issues are ones that come to the forefront of public interest and policy debates most often today, there is another, even more important, way in which water shapes

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One contribution of 14 to a Discussion Meeting Issue 'Water and society: past, present and future'.

human life and society. The interactions of water flowing across the land with human social actions—especially land-use practices—has been transforming the Earth's landscapes in dramatic ways for up to 10 millennia. These transformations have altered topography and coastlines, changed river courses and caused lakes to disappear, destroyed subsistence productivity for some and enhanced it for others. Geologist Bruce Wilkinson (2005) recently calculated that anthropogenic changes to the Earth's surface now exceed non-anthropogenic ones, with current erosion rates an astounding 28 times greater than the pre-human average, leading him to suggest that the present should be called the 'Anthropocene'. While mining and construction are visually obvious ways that humans reshape the world, Wilkinson notes that the interactions between human agropastoral practices and surface water are much greater at a global scale, with an impact that is more than double that of all other surface-altering activities.

2. Water, land use and landscapes

There is a delicate balance between the amount and velocity of water flowing over the Earth's surface, the slope of the surface and the cohesion of surface sediments. It determines whether the water will entrain, transport or deposit sediments and the size of particles affected (from dust to boulders). By the comparatively simple acts of clearing or changing vegetation, cultivating the soil and altering local topography, humans alter this balance. All farming involves alteration of naturally occurring vegetation to favour those domestic species that provide most of the edible biomass for humans, and often requires clearing all natural vegetation and replacing it with human-sown taxa. This alters the subsurface network of plant roots that bind surface soils, potentially increasing erosion risk. In fact, the act of cultivation itself reduces biophysical cohesion of soils at scales ranging from the point locations of digging stick holes to the many hectares of mechanically ploughed fields. Terracing and check dams across small drainages reduce the flow velocity of surface water and alter the local slope.

Animal husbandry has different but equally important effects on vegetation. If the numbers of animals on a patch of land are few, vegetation growth may be able to keep up the losses due to grazing. However, in order to maximize herding returns and to maintain better control and protection of their herds, societies often keep so many animals in an area that they remove vegetation faster than it can regrow; if the domestic animals are not periodically moved to new pastures, they can completely denude a landscape. Furthermore, an important economic benefit of domestic animals is that they can transform inedible and otherwise unusable plant biomass into human-consumable food and raw materials—especially in sparsely vegetated arid and semi-arid zones. However, these arid landscapes are protected from infrequent but heavy seasonal rains by this sparse vegetation, which regrows very slowly, and is easily stunted by excessive grazing. On the other hand, animal manure can add nutrients to cultivated soils, allowing farmers to cultivate a single patch more intensively, reducing or even eliminating the need for fallowing. Finally, the hooves of domestic animals can physically disturb the cohesion of surface sediments, especially when they are pastured in higher concentrations and have significantly removed protective vegetation.

In such ways, even the decisions and actions of technologically unsophisticated pre-historic subsistence farmers have shaped Earth's landscapes. Flowing water amplifies human land use, so that even small-scale farming practices can have effects that are far reaching and difficult to predict. Over long time frames, the additive consequences of day-to-day farming decisions can result in a dramatic reshaping of the landscape, or they can help to inhibit landscape change. The diverse geomorphological consequences of human decisions have equally important social ramifications; by transforming the landscape, the interactions of humans and water alter its productive potential, and the most basic economic contexts of societies.

In the abstract, the ways in which flowing water can entrain, transport and deposit sediment have been studied in detail, and are described by well-understood physical laws. However, the real-world application of these principles across terrestrial surfaces of variable topography, land cover and soils is much more complex—and this complexity is compounded by adding in human land use (including crops and domestic animals) and the recursive effect of landscape changes on agricultural productivity, with repercussions for social organization and practice. The diversity of components in these socio-ecological systems (SESs)—people, crops and wild plants, domestic and wild animals, soils, topography, rainfall and groundwater—the importance of interactions among these components compared with their individual properties, the fact that long-term geomorphological and economic consequences cannot be predicted in a linear fashion by the nature and magnitude of land-use practices and the tendency for these SESs to evolve continuously over time are all typical characteristics of complex adaptive systems (CASs) (Simon 1962; Janssen 2002; Bentley 2003; Cho 2009; Ostrom 2009).

As archaeologists, we seek a better understanding of the social and natural drivers of long-term change in human systems. The characteristics inherent in CASs in general and SESs in particular make this a difficult endeavour for modern societies and landscapes that we can observe in detail. But the archaeological record is composed of the scattered, fragmentary, static residues of dynamic, complex SESs, of which archaeologists are able to recover only a tiny fraction in practice. For this reason, we and others have turned to new methods of computational modelling to help us study the multi-dimensional interactions of humans with each other and the biophysical world—including water flowing across landscapes (Axtell *et al.* 2002; Berry *et al.* 2002; Parker *et al.* 2003; Grimm *et al.* 2005; Kohler *et al.* 2005; Clevis *et al.* 2006; Kohler & van der Leeuw 2007).

As real-world examples of CASs, these SESs often are not adequately represented by traditional mathematical equations, which can fail to capture their more subtle and complex properties—especially their diversity and dynamics across space and time. Rather than try to characterize a complex SES with a set of deterministic mathematical laws, a computational modelling approach seeks to create a laboratory-like setting in which carefully controlled experiments can be carried out to identify likely ranges of outcomes given alternative sets of initial and boundary conditions (Bankes 2002; Bankes *et al.* 2002). Computational modelling is a methodology with an exciting potential for experimentally simulating aspects of past societies in order to test alternative explanations for long-term change. Moreover, comparing the results of such computational

experiments with the archaeological record of real-world societies offers a way to cumulatively improve models of SESs, a point we return to at the end of this paper.

3. A computational modelling laboratory for SESs

In the Mediterranean Landscape Dynamics project (MedLand), supported by the US National Science Foundation,¹ an interdisciplinary team of scientists have worked to develop a computational modelling laboratory for studying the long-term dynamics of land-use–landscape interactions in SESs across the Mediterranean. We selected intensive study areas in eastern Spain and western Jordan for building and testing the modelling laboratory, representing the range of social and ecological contexts spanning the ancient (and modern) Mediterranean. Our focus is on the dynamic processes and socio-ecological consequences of the beginning of agropastoral systems—from the earliest Neolithic to the beginnings of Bronze Age urbanism. In this paper, we offer a brief overview of our team's work to date on this new research environment for studying SESs.

The computational laboratory is structured in a modular fashion as a hybrid modelling and simulation environment (Mayer *et al.* 2006; Mayer 2009; Mayer & Sarjoughian 2009). There are a number of ways to model dynamic systems computationally, with varying strengths and weaknesses. Different subsystems of an SES may be better represented by different approaches to modelling and simulation. In the MedLand laboratory, landscape and related biophysical processes are modelled using a cellular automata approach, implemented in a raster geographical information system (GIS), whereas human land use and related decision-making is modelled through agent-based simulations. Contributing models include regression-based simulations of past climate and regional vegetation. A set of Java libraries provides the visualization engine. Finally, an overarching interaction module ensures correct integration of all the modules of the laboratory.

4. Modelling dynamic landscapes

There are various, well-known ways of expressing mathematically the way in which water flows and its capacity to erode, transport and deposit sediments (Degani *et al.* 1979; Mitasova *et al.* 1996; Mitas & Mitasova 1998; Mitasova & Mitas 2001*a,b*; Warren *et al.* 2005; Clevis *et al.* 2006; Peeters *et al.* 2006; Singh & Phadke 2006). We use a transport-limited algorithm to represent the flow of water over land surfaces, based on concepts described by Kirkby (1971) and adapted for two-dimensional surfaces by Moore & Burch (1986). This algorithm was further modified by MedLand team member Helena Mitasova (Mitasova *et al.* 1996) to be operationalized in a realistic, three-dimensional terrain of a raster GIS environment (see below). Moore and Burch originally referred to this algorithm as 'unit stream power erosion/deposition' or USPED. However, as we implement this model in the MedLand computational laboratory, the phrase USPED is somewhat misleading because the algorithm actually models the geomorphological processes

¹NSF grant BCS-0410269.

that are characteristic of small watersheds (hill slopes, rills and gullies) rather than of streams or rivers. In fact, the algorithm is not particularly applicable to larger streams and rivers at all (Warren *et al.* 2005); hence, we refer to it here as the hill slope erosion/deposition model or HED (Barton *et al.* 2010). We have re-expressed Mitasova's equations in the MedLand laboratory as a recursive computational routine that simulates high-resolution landscape change across the four coupled dimensions of space and time; we also have extended the HED algorithm with equations that do represent sediment entrainment, transport and erosion in small- to moderate-sized streams.

As operationalized by Mitasova and colleagues, the HED algorithm combines the environmental parameters of the universal soil loss equation (USLE/RUSLE) with an estimate of water flow derived from the local gradient and the upslope contributing area per unit contour width at each cell of a raster (see below) GIS landscape. By taking the partial derivatives of these flow values, we can then calculate the change in sediment transport capacity from one cell to the next, and thus the amount of erosion and deposition that would occur at each raster cell (Wischmeier *et al.* 1971; Wischmeier & Smith 1978; Degani *et al.* 1979; Mitasova *et al.* 2001, 2004; Flanagan *et al.* 2003; Warren *et al.* 2005; Singh & Phadke 2006). The HED algorithm is the core of our model for simulating landscape dynamics in the Mediterranean basin, and is potentially useful for many other settings in arid, semi-arid and xeric regions.

As mentioned above, we are creating a computational simulation model of dynamic, multi-factored landscapes in the environment of a raster GIS. While rasters are the oldest GIS format (dating to the SYMAP, GRID and ODYSSEY mainframe programs of the 1960s and 1970s), a raster GIS is less well known among archaeologists and other social scientists, who more commonly use vector formats that represent spatial information as points, arcs and polygons (Wheatley & Gillings 2002; Conolly & Lake 2006). Nevertheless, raster formats are ideal for digital management and analysis of much spatially referenced ecological data, and are especially useful for geospatial modelling of landscape change.

In a raster GIS, a continuous surface (like a landscape) is represented by a matrix of equal-sized cells (usually square), with each cell assigned a value corresponding to a parameter of interest. In a digital elevation model (DEM), for example, each cell is assigned the elevation of the corresponding parcel of terrain represented by the raster cell in the GIS. Alternatively, for a vegetation map, each cell is assigned a value to indicate the dominant vegetation community in that landscape parcel. Raster cells can be any size depending on the need for accuracy (smaller cells) or computational efficiency (larger cells). For landscape modelling, we use cells of 15×15 m—a comparatively high resolution for many GIS applications.

The slope and aspect (direction of slope) of each cell can easily be calculated from a raster DEM. More sophisticated algorithms, often called hydrology or flow models, can calculate the amount of water that would accumulate on each cell from the amount of rain falling on a landscape and the way in which water would flow down the slopes of each cell. Multiple, overlaid, raster maps can be combined using *map algebra* such that the values in the cells of a resultant calculated map are the product of an algebraic equation using the values of the geographically corresponding cells of the input maps.

Our HED model combines maps of slope, aspect, soil erodibility, soil thickness, land cover, flowing water accumulation and rainfall to calculate the erosion/deposition in each landscape cell during each iteration of the model. These erosion/deposition values are added back to a DEM of topography to create a new landscape after a cycle of land use and landscape change, and the process is repeated. The erosion/deposition values are also subtracted/added to the map of soil thickness; if soil thickness drops to zero, soil erodibility becomes equal to bare rock.

We use the open-source GRASS GIS software (<http://www.osgeo.org/grass>) for modelling landscape dynamics. GRASS (GRASS Development Team 2009) is a full-featured GIS that has sophisticated, computationally efficient and easy-to-use raster modules (Neteler & Mitasova 2008) that run on all common desktop computer platforms. GRASS is open source and available free of charge, allowing us to make the MedLand modelling laboratory available to researchers globally. Importantly, all GRASS functions can be combined and automated easily in many scripting languages. This makes it possible to iterate many cycles of land use and landscape change, simulating SES dynamics over centuries. Using GRASS, a complete cycle of erosion/deposition in our model can be simulated for a landscape of 1.5 million cells in less than a minute on a modern desktop computer. Our scripts are written in Python, an open-source object-oriented language widely used in the sciences (<http://www.python.org>) and available for all common desktop computer systems. Current versions of the MedLand landscape modelling scripts for GRASS can be downloaded from <http://svn.osgeo.org/grass/grass-addons/LandDyn/>, and a detailed description of the HED algorithm and its implementation for dynamic landscape modelling is presented in Barton *et al.* (2010).

5. Modelling human land use

(a) Stochastic modelling

We use two different approaches to represent human land-use decisions and practices in the MedLand computational modelling laboratory. In initial experiments, including those discussed here, we have used a stochastic algorithm to simulate land use. Most recently, these have focused on the Wadi Ziqlab watershed of northwest Jordan (figure 1) as a test case for comparing the long-term consequences of different combinations of intensive cultivation, shifting cultivation with a 5-year fallow cycle and ovicaprine grazing around settlements of different sizes (Bascompte 2009).

We begin by calculating catchments for cereal cultivation and grazing, a multi-step process automated in a GRASS script (figure 2). Building on work by Hill (1998) and ethnoarchaeological studies of small-scale horticulture in southwest Asia (Allan *et al.* 1972; Watson 1979; Kramer 1980, 1982; Kamp 1987; Falconer *et al.* 1994), we calculate the total hectares of cereal cultivation needed to support a village of a given number of inhabitants. This is the amount of land needed for intensive cultivation (i.e. repeatedly cultivating the same plot, without fallowing, using techniques like manuring and crop rotation to maintain fertility). For shifting cultivation, we multiply the total cultivation area required by the number of years in the fallow cycle (i.e. the time that a field will lay fallow on average).

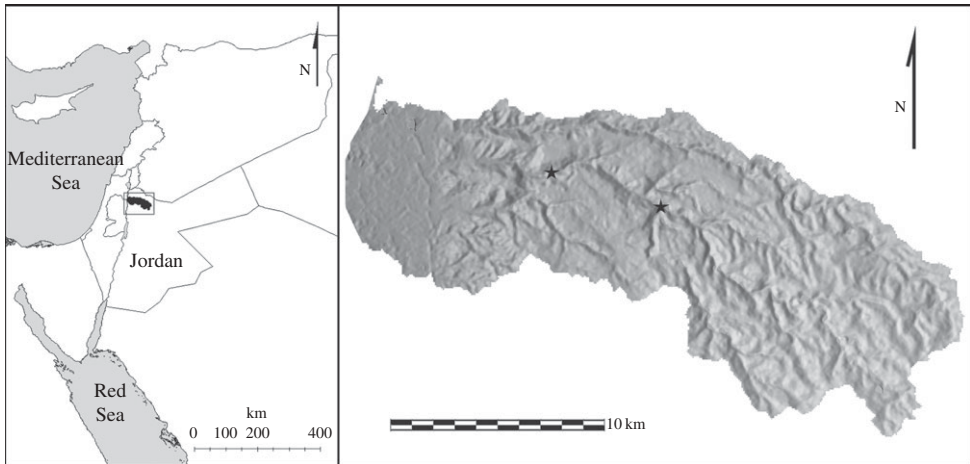


Figure 1. Location of Wadi Ziqlab study area (after Barton *et al.* 2010).

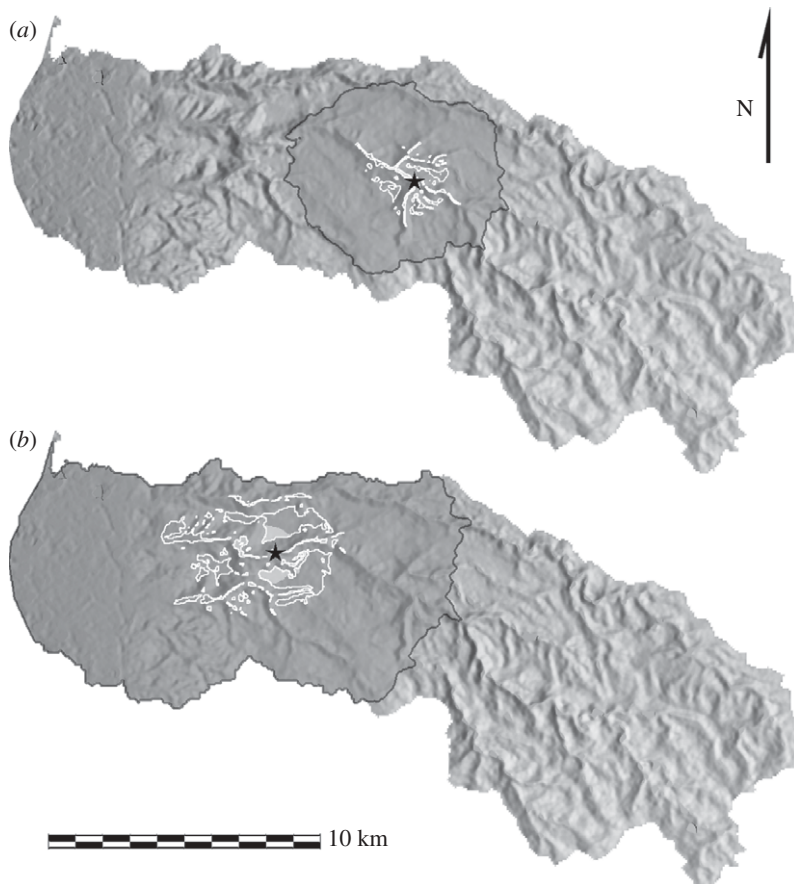


Figure 2. Agropastoral catchments around pre-historic Neolithic sites of (a) Tabaqat al-Bûma and (b) Tell Rakkan.

With a 5-year fallow cycle, for example, it is necessary to include five times as much land in the cultivation catchment than is required for intensive cultivation because only one-fifth of the land is cultivated at any one time. We similarly calculate the total hectares needed to support the herds of a village. We assume that flocks will be moved regularly and a patch of land will not be grazed year after year. With the stochastic land-use model described above, we assume that only one-third of the land is grazed in any year (the equivalent of a 3-year pasture rotation), giving a grazing catchment that is three times the size of the minimum amount of land needed for the village flocks. The modelling laboratory permits experiments in which the length of fallow cycles and the intensity of grazing can be varied from the values we use here in order to study the effects of differences in land-use practices on landscapes.

Finally, for each catchment, we identify the raster cells that (i) together meet the area requirements for intensive cultivation, shifting cultivation and/or grazing, (ii) minimize the time and effort needed to walk across the terrain to and from the village, and (iii) have a slope of 10° or less for cultivated lands (Bevan & Conolly 2002). It is important to keep in mind that farmers had to walk to their fields and carry the harvest back to their settlement, so the distance of a field from the village is important. We use least-cost algorithms in the GIS to calculate this (Barton *et al.* 2010).

When carrying out the land-use/landscape experiments described here, simulating intensive cultivation means that all cells in the agricultural catchment are treated as cultivated. For shifting cultivation with a 5-year fallow cycle, a randomly chosen 20 per cent of the cells in the agricultural catchment are considered cultivated each cycle. To simulate a grazing intensity of one-third of the landscape being grazed at one time, a random selection of 33 per cent of the uncultivated cells (including fallowed fields) in the grazing catchment is considered grazed each cycle. A new random selection of landscape cells is made in each cycle for shifting cultivation and/or grazing, simulating farmers clearing new fields and moving herds.

Based on published palaeoenvironmental research, we model the region of this test case in northwest Jordan as initially covered in Mediterranean woodland during the Early Holocene (Kohler-Rollefson & Rollefson 1990; Banning 1995; Hunt *et al.* 2004). In our landscape evolution model, the abilities of particular vegetation (land cover) and soil types to resist or promote sediment detachment due to flowing water are responsible for most of the variation in erosion and/or deposition. The RUSLE parameters used in the HED modelling algorithm for the erosion resistance of land cover (*C*-factor) and soil (*K*-factor), along with rainfall intensity (*R*-factor), are well known and have been calculated empirically for a variety of settings, including Mediterranean landscapes (Renard & Freimund 1994; Renard *et al.* 1997; Martínez-Casasnovas & Sánchez-Bosch 2000; Essa 2004; Hammad *et al.* 2004; Boellstorff & Benito 2005). In the modelling laboratory, when a field is cleared for cereal cultivation, the *C*-factor for vegetation in the corresponding landscape cell is changed from that of Mediterranean woodland to that of wheat/barley agriculture (the equivalent of sparse natural grassland). Unlike cultivation, grazing does not immediately remove all vegetation, but instead continually reduces vegetation cover the longer a particular patch is grazed. Hence, each time a cell is selected for grazing, its erosion resistance (i.e. *C*-factor) is reduced by 4 per cent. Any cell that is not cultivated or grazed will

regain land-cover-related erosion resistance (as if vegetation were regrowing) at a rate of 2 per cent per annual cycle—corresponding to Mediterranean vegetation succession rates measured in abandoned fields (Bonet & Pausas 2004, 2007).

(b) *Agent-based modelling*

Stochastic modelling works well for controlled experiments in which we wish to understand the outcomes of different land-use practices in a complex SES. However, farming households do not select land to farm and graze randomly, but base their land-use decisions on a combination of many factors, such as the economic results of past land-use decisions, the availability of labour in the household to clear and cultivate fields or manage flocks, their perception of the potential yield of a plot of land, the energy requirements to make a patch of land productive and the actions of other members of the community. Moreover, the specific mix of decision factors will vary for each household in a community, and from year to year.

Agent-based modelling (ABM) provides an effective methodology of simulating independent, but interacting, households, who make decisions on the basis of rule-based (e.g. including norms and risk) assessments of internal and external conditions (Axtell *et al.* 2002; Bankes 2002; Bankes *et al.* 2002; Kohler *et al.* 2005). In ABMs, multiple autonomous software agents are created with rules for formulating decisions and means for sensing their environment. They are instantiated ('activated') on virtual landscapes and allowed to act and interact over time without intervention by the researcher. This provides a more realistic experimental environment than that of stochastic modelling, though with a loss of some degree of control. While ABMs can be created in any computational platform (even in an Excel spreadsheet!), object-oriented programming languages (e.g. Java, Python, C++) have been used most successfully for this type of modelling environment. Currently, we are using the DEVS-Suite platform, implemented in the Java programming language (Sarjoughian & Zeigler 1998).

In the agent-based model that is currently in development and testing for the MedLand laboratory (Mayer *et al.* 2006; Mayer 2009), each agent is a household rather than an individual person. Households are grouped into villages and must remain in the village where they are initially instantiated. Village location is chosen by the researcher and does not change during the course of a simulation. In future versions of the laboratory, we plan to allow villages to move and/or households to move among villages.

After initialization, each household in a village chooses plots of land by scanning the landscape surrounding a village for land not currently owned by other households. Each household also looks at the result of the previous year's subsistence activities to determine whether it needs to cultivate more or less land than it did previously, and decides how many patches to cultivate or fallow. The number of patches of land that a household can cultivate is limited by the labour available in the household, which is a function of the number of adults in the household. The household then evaluates the suitability of available new patches of land to cultivate on the basis of fertility, slope, soil depth and distance from a village to estimate potential future yield and the cost to cultivate the land. Based on this evaluation, the household agent selects the best plots available in terms of net return (yields minus costs). Once parcels are chosen to be cultivated,

the household clears the land (i.e. sets their land-cover value to that of sparse grassland as described above) and cultivates it. Every cycle that a patch of ground is cultivated, its fertility drops by 2 per cent. Fallowed land regains natural vegetation (and its ability to limit erosion) at the same rate of 2 per cent per year and regains fertility at the rate of 1 per cent per year (Bonet & Pausas 2004, 2007).

Land is chosen for ovicaprine grazing in a similar way. Households evaluate land on the basis of its current vegetation (important for grazing returns) and distance; fertility, soil depth and slope are unimportant. Only non-cultivated land is grazed, though this can include fallowed land. The vegetation of grazed cells is reduced at a rate that is a function of the number of animals per hectare above a steady-state grazing rate calculated from the ethnographic and agronomic research literature (Lubbering *et al.* 1991; Al-Jaloudy 2006). Herd grazing density (i.e. the number of animals per hectare) and the division of household labour into cultivation or grazing are set by the user rather than the agents. Likewise, the herd composition for each household (i.e. the ratio of sheep to goats within each household's ovicaprine population), which can vary greatly with social and environmental circumstance, is also set by the user at the onset of the simulation (Wilson 1982; Rollefson & Kohler-Rollefson 1989; Khazanov 1994; Garrard *et al.* 1996; Blench 1998). Herd size is based on the number of individuals in each household, and the amount of necessary land for each household's ovicaprine herd is based upon the size of the herd, herd composition and herd grazing density (Khazanov 1994; Blench 1998).

The annual yield of crops for a patch of land is determined by the soil fertility and depth, estimated from agronomic research and ethnographic studies of subsistence farming in the Mediterranean region (Thomson *et al.* 1986; van der Veen & Palmer 1997; Araus *et al.* 2001; Sadras & Calvino 2001; Troccoli & Codianni 2005). As noted above, the fertility of a patch decreases or increases as a patch is cultivated or fallowed, and the soil depth decreases or increases owing to erosion or deposition as calculated by the HED model. The return on grazing for each cell is a function of the number of animals grazed and the amount of vegetation on that patch of land. The success or failure of the annual harvest affects the demography of households and villages. Good harvests increase the likelihood of births and decrease the likelihood of deaths within a household; poor harvests have the opposite effects.

Human (i.e. agent)-generated changes to land cover for clearance, cultivation, grazing or fallowing are transformed into a raster GIS map with land-use values in each cell. These values modify the land-cover map to create a new vegetation map. The HED model is then run with the new land-cover map, creating a new DEM and a new soil thickness map as described above. Similarly, for every cycle that a patch is left fallow, its fertility increases and its natural vegetation grows back as described above. The information in these new maps is then used by the agents when making land-use decisions for the next cycle.

(c) *Model control and sequencing*

Although model cycles can represent any units of time, in most of our modelling to date, a cycle represents a single year. Thus, the catchments used delineate the zone of human–environment interaction encompassing all the territory that

villages would use over the course of an entire year. Similarly, natural processes (rainfall, erosion/deposition, vegetation regrowth) are also simulated at an annual interval.

During each cycle of the stochastic land-use model, randomly selected patches of land cover are changed within catchments that were calculated from user input about the location and size of settlements and the nature of land use practised (e.g. intensive cultivation, shifting cultivation, grazing). Thus stochastic land-use modelling results in a series of land-cover maps—one for each cycle of the simulation. Subsequently, the HED model is run for the same number of cycles as the land-use simulation, using the previously generated series of land-cover maps as input, along with values for maps of rainfall intensity, soil erodibility and initial soil thickness. This allows for a wide variety of land-use/landscape experiments to be carried out in which different environmental and land-use parameters can be controlled and systematically varied. As we discuss below, the results can be surprising and are not easily predicted from the input parameters. The drawback of this protocol is the lack of feedbacks between landscape change, land cover and land-use practices. Such feedbacks are common in SESs, and modelling these processes is important for understanding the consequences of the complex interaction between humans and water.

Coupling an ABM of households with the HED and succession models in a GIS permits some of the more critical of these feedbacks to be simulated in the laboratory. However, it also introduces new complexities in the interactions and timing of the different model components. For this reason, we have an explicit interaction module that controls the way in which the ABM is coupled with the GIS (Mayer & Sarjoughian 2007, 2009; Mayer 2009). This interaction module controls linkages between models, synchronizing the timing of HED cycles in the GIS to land-use cycles in the ABM, matching the scale of land use in the ABM (i.e. fields) to corresponding raster cells in the GIS, and calling the routines of the visualization system described below.

6. Visualization

The land-use/landscape dynamics modelling laboratory produces multiple GIS maps for each cycle of a simulation. These include raster maps of net erosion/deposition, topography (i.e. a DEM), soil thickness, vegetation and its effects on erosion resistance (i.e. *C*-factor for the RUSLE equation), and locations of patches cultivated or grazed, as well as soil fertility and land-use activity maps for the ABM version. Cumulative maps of erosion/deposition also can be produced. All these maps can be displayed within the GIS environment or exported for viewing in other software. This type of visualization is useful for many kinds of analysis. However, it also can be valuable to see the dynamics of land-use/landscape interactions as they happen in the modelling laboratory, especially when land use is represented by independently acting computational agents. Our simulations take place at a speed that makes this feasible. Such visualization is complicated, however, by the fact that the ABM is a Java-based application that is running independently of the C-language-based GRASS GIS that is handling the landscape dynamics modelling. We have been able to solve this dilemma by using NASA's World Wind software (Maxwell *et al.*

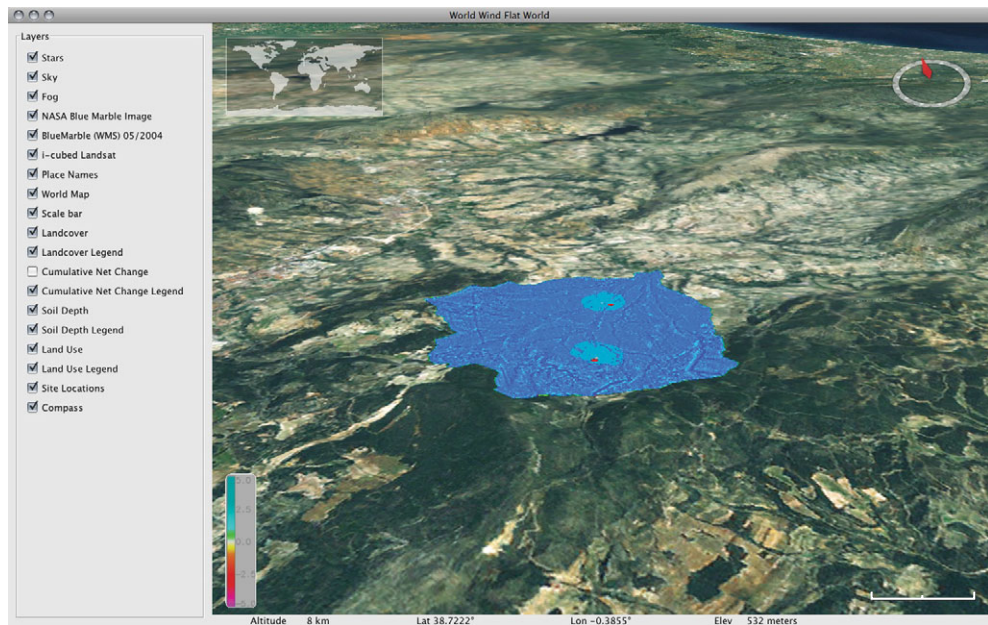


Figure 3. World Wind visualization of coupled ABM/GIS model of agropastoral land use in the Penaguila Valley of eastern Spain. Scale bar, 2000 m.

2009) to display the results of hybrid ABM/GIS modelling of land use and landscape change (figure 3). This open-source software is functionally similar to the commercial package Google Earth, in that it permits public geospatial data (e.g. topographic DEMs and satellite imagery) to be acquired over the Internet and combined with locally generated geospatial data. In the MedLand modelling laboratory, we have provided an option that automatically exports maps of potential interest (e.g. erosion/deposition, vegetation, land use, soil depth) to easily read PNG files each cycle. We have modified the World Wind Java code to display these PNG files over topography and satellite imagery acquired over the Internet. Land-use/landscape interactions can then be viewed as they are simulated in the laboratory, and overlaid onto a real-world landscape, making it possible to visually track spatial relationships between land-use practices of household agents and changes in topography, soils and vegetation.

7. Initial results

The ABM module of the MedLand Land-use/Landscape Dynamics Modelling Laboratory is currently in active development and nearing completion. Initial testing of this module has been focused primarily on its overall functionality and ability for the ABM to be coupled dynamically with the GIS-based landscape models (figure 4). The stochastic land-use simulation module, while still undergoing improvements, has been functional for the past year, permitting us to carry out controlled experiments in the complex interactions of water-mediated interactions between human land use and landscape change.

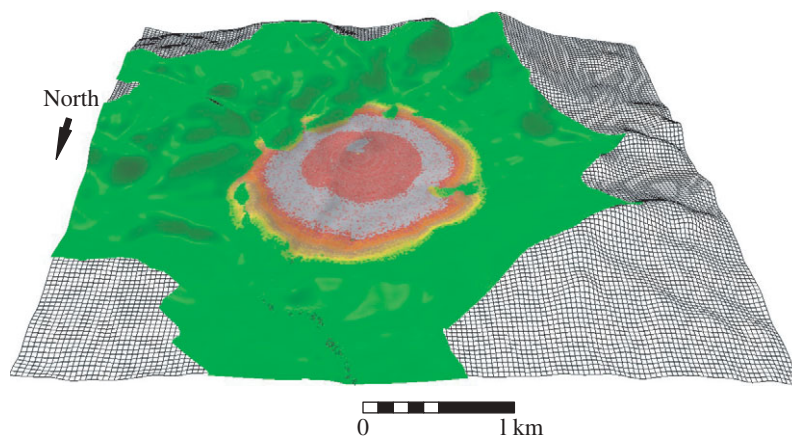


Figure 4. Coupled ABM/GIS model of agropastoral land use and its impacts after 100 years around a Neolithic hamlet in the watershed of the Río Penaguila valley of eastern Spain. Colours represent land cover: green is unmodified Mediterranean woodland; brown to yellow indicates regrowing woodland; orange tones include matorral-type shrubs; red is herbs, grasses and sparse shrubs; light red is cereal agriculture (grasses); and grey is denuded to very sparse grasses and herbs. Topography is reconstructed early Holocene terrain, based on Terra/ASTER GDM imagery.

In the most recent set of experiments, we used data from two known pre-historic Neolithic settlements in the Wadi Ziqlab (figure 2), Tell Rakkan and Tabaqat al-Bûma, to build a model that simulates the long-term effects of different kinds of land-use practices for small-scale, subsistence agropastoralism (Barton *et al.* 2010). In Wadi Ziqlab, people lived in small villages (approx. 5–20 families) during the Pre-Pottery Neolithic B (PPNB, 9500–7900 BP) and Pre-Pottery Neolithic C periods (7900–7500 cal. BP), but abandoned these villages in the subsequent Late Neolithic (LN) period (7500–6100 BP) when they lived in dispersed farmsteads (approx. one to five families) (Banning 1996; Simmons 2007). In addition to this change in settlement patterns, stone tool technology became simpler. The complex of specialized blade-core technologies of the PPN was replaced by an LN technology that centred around expedient flake tools (Kadowaki 2005). The LN period also sees the introduction of pottery, which, in this period, consists of mainly coarse-fired utilitarian vessels and only a relatively few decorated pots (Gibbs 2006). The two settlements used as a basis for our modelling—the PPNB village of Tell Rakkan and LN hamlet of Tabaqat al-Bûma—have been studied by Banning and colleagues (Banning 1996).

In these experiments, we simulated the effects of land use around settlements of different sizes, calculating the size of the land-use catchments around each on the basis of the average number of people who would have lived in PPNB villages and LN hamlets, respectively. We then modelled four types of land-use (intensive or shifting cultivation, with or without grazing), which are plausible for both PPNB and LN subsistence practices (table 1). We also varied the time over which we measured the impacts of different land use, examining the effects after 40 years (i.e. simulation cycles) and 200 years. That is, we compared the landscape

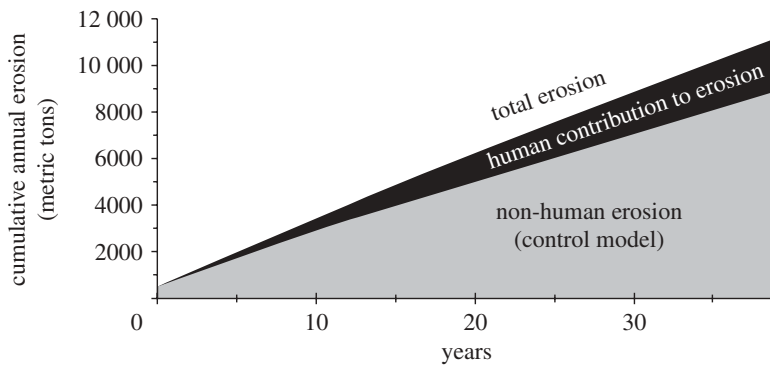


Figure 5. Comparison of anthropogenic and non-anthropogenic erosion modelled for shifting cultivation and grazing in the catchment of a small agricultural village in the Wadi Ziqlab.

Table 1. Experiments in land-use/landscape interaction (adapted from Barton *et al.* 2010).

settlement	precipitation and soil	agropastoral land-use experiments	
small village (like Tell Rakkan <i>ca</i> 8400 cal. BP)	918.5 mm yr ⁻¹ <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
		shifting cultivation	grazing
hamlet (like Tabaqat al-Bûma <i>ca</i> 7400. cal. BP)	783.7 mm yr ⁻¹ <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
		shifting cultivation	grazing

consequences of alternative land-use practices within the two-generation span of active memory in a pre-literate society with the consequences over a time span of 10 generations, extending into the legendary past.

Importantly, we carried out baseline *control* experiments around the modelled settlements (figure 5). These are essential for understanding the impacts of human actions on ecosystems. At best, archaeological and palaeoecological proxy data for past landscapes can only tell us what actually took place in small areas at snapshots in time. In the case of the pre-historic SESs of northwest Jordan, the proxy record mainly documents human-occupied landscapes and anthropogenic changes. However, landscapes are highly dynamic even without a human presence. To accurately measure the impacts of *human* land use, we need to compare the same landscapes with and without human inhabitants and their agropastoral practices. Such *contrafactual palaeoecology* is impossible with proxy data, but can be done easily in a computational modelling laboratory, so that the effects of non-human ecodynamics (e.g. rain falling on a vegetated terrain, resulting in patterns of erosion and deposition) can be compared with human socio-ecological dynamics. This permits us to express our experimental results in terms of net human contribution to landscape change.

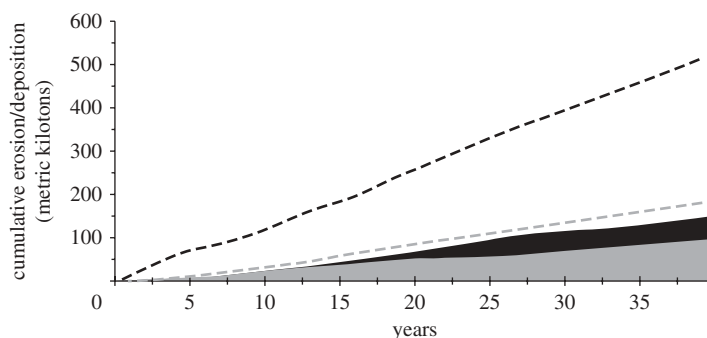


Figure 6. Forty years of anthropogenic erosion and deposition modelled for landscapes around farming hamlet in the Wadi Ziqlab. Black-shaded area, deposition in village catchment; grey shaded area, deposition in hamlet catchment; black dashed line, erosion in village catchment; grey dashed line, erosion in hamlet catchment.

As might be expected from the experimental design shown in table 1, even this initial work has generated a large amount of data (Barton *et al.* 2010). Here, we briefly review one set of results with potential significance beyond archaeology and the origins of farming: a possible phase shift in landscape impacts when a threshold in community size is passed. It is not surprising that larger communities should have a larger impact on landscape change than smaller communities. Common sense would suggest that the relationship between the growth of human settlements and their landscape consequences should be a scalar one, since larger communities have more people altering the landscape by cereal cultivation and ovicaprine grazing. However, CASs—and especially SESs—often exhibit non-linear relationships of causality, and that appears to be the case for the agropastoral systems whose dynamics we are modelling in our computational laboratory.

The small hamlet was modelled after the Pottery Neolithic archaeological site of Tabaqat al-Būma, with three households and 20 inhabitants. The PPNB village of Tell Rakkan, with 15 households and 100 inhabitants, served as a model for the larger settlement. While different combinations of cultivation and grazing affected the amount and distribution of landscape erosion and sediment deposition around the small hamlet in different ways, the presence or absence of grazing had a much greater impact on landscape dynamics than whether intensive cultivation or shifting cultivation was practised (figure 6). In addition to increasing erosion, the combination of grazing with cultivation also increased total deposition to a large degree. In the 40-year simulation of grazing and shifting cultivation, the gain of anthropogenic sediment deposition totalled over 50 per cent of the amount of sediment lost due to anthropogenic erosion. Moreover, because much of the erosion was a result of ovicaprine grazing, it largely affected uncultivated uplands, where it had limited effects on agropastoral productivity—especially for shrub- and tree-browsing goats. On the other hand, the accompanying increased deposition took place primarily in wadi bottoms—the primary area for cultivation around this tiny hamlet—increasing potentially arable lands and productivity. In other words, an important effect

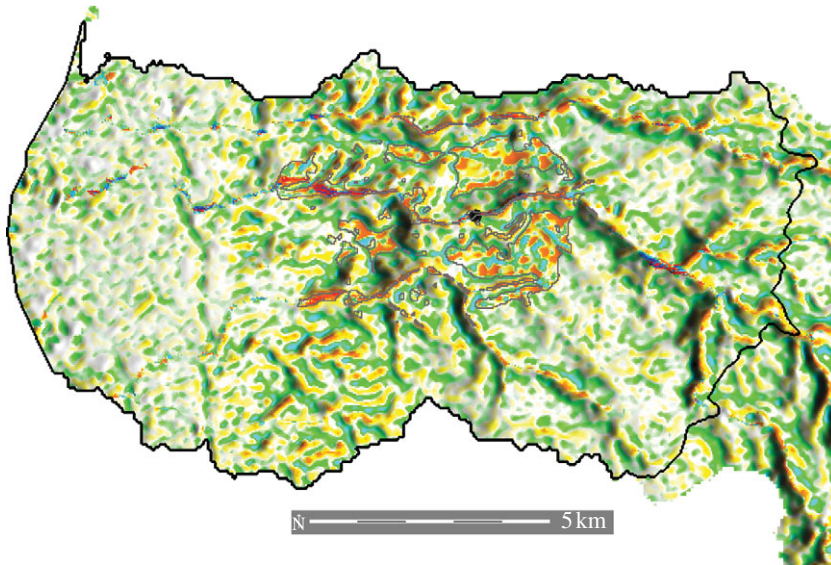


Figure 7. Cumulative erosion and deposition around village modelled from PPNB Tell Rakkan after 40 years of shifting cultivation and ovicaprine grazing.

of anthropogenic landscape change on simulated SES is to increase potential agropastoral productivity around tiny hamlets that add ovicaprine grazing to either intensive or shifting cultivation. Demographic growth is one likely biosocial consequence of this apparently successful land-use strategy of combining cereal cultivation in well-watered wadis with ovicaprine grazing in the surrounding uplands. Indeed, the growth of Neolithic settlements, sometimes to large towns of hundreds of inhabitants, characterizes the archaeological record of western Jordan and adjacent areas over the course of the Pre-Pottery Neolithic (Kuijt & Goring-Morris 2002; Simmons 2007).

Because of the CAS nature of this SES, however, increasing community size did not translate into greater net agropastoral productivity. For the larger village in our simulation experiment, shifting cultivation rather than grazing had the biggest impacts on net anthropogenic erosion and deposition. That is, the most significant erosion around large settlements took place in cultivated zones, decreasing their productivity through soil loss (figure 7). While some of this lost soil was redeposited, the ratio of soil loss to newly deposited sediment in a 40-year simulation was nearly twice that of the small hamlet (3.45 compared with 1.88), exacerbating the fact that much of the soil was lost from areas where it reduced agropastoral productivity. Furthermore, we found that, if we ran the experiment for 10 generations (200 years), the rate of erosion around the larger settlement continued to exceed deposition by a significant amount over time, resulting in cumulative and steadily growing loss of productive capacity (figure 8).

In other words, farmers practising a successful strategy of land use that combined shifting cultivation with ovicaprine grazing, and who allowed their community to grow in response to increased agropastoral productivity, would find that the successful practices of prior generations resulted in declines in

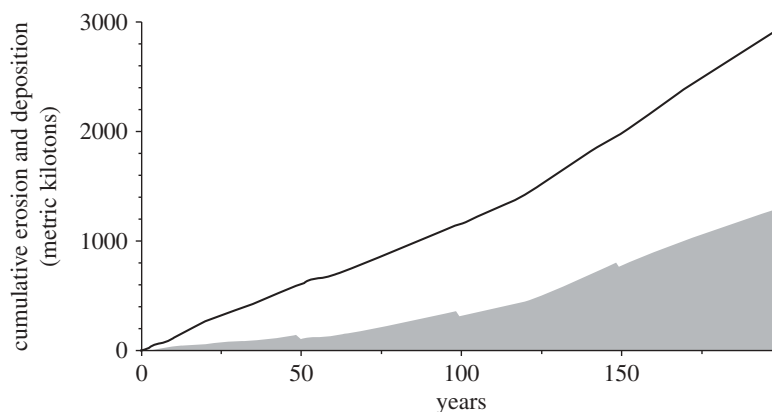


Figure 8. Two hundred years of anthropogenic erosion in catchment around village modelled from PPNB Tell Rakkan. Grey-shaded area, deposition; black line, erosion.

productivity that became increasingly more severe over time. In the context of our models, the only recourse for this economic crisis was to reduce community size to small hamlets or increase the amount of grazing relative to cultivation, in order to move the impacts of erosion out of the cultivated zone and increase the amount of new sediment deposited in cultivated areas. These results from our modelling parallel the archaeological record of early farming societies in Southwest Asia. Many early farming settlements grew in size during the PPN but were abandoned by the terminal PPN. In northern Jordan, villages and towns of the PPN were replaced by much smaller settlements, like Tabaqat al-Bûma during the LN, while southern Jordan saw an increased emphasis on grazing (Rollefson & Kohler-Rollefson 1992; Legge & Harris 1996; Martin 1999; Kuijt & Goring-Morris 2002; Quintero *et al.* 2004; Simmons 2007; Twiss 2007; Rosen 2008).

A third alternative we have not yet modelled would be to intensify agriculture through a variety of conservation practices, like terracing, that can require organized, pooled labour and investments in landesque capital. Often such intensification has been accompanied (as both cause and effect) in past societies by the growth of inequalities in social prestige and power. This kind of response is seen in the LN archaeological record of Mesopotamia.

8. Discussion

While direct human control of water for irrigation, flood control and drinking has clearly been important for human societies, and especially so since the beginning of agriculture over 10 000 years ago, indirect human interaction with terrestrial surface water has played a much greater role in effecting anthropogenic transformations to the world in which we live. Yet, even though these transformations can be profound and regionally extensive, they often are not easily observable even during the comparatively long human lifespan. The consequences of human–water interactions may not be easily recognizable even after the fact, and in many cases require sophisticated geoarchaeological studies to document their existence.

The Mediterranean is a notable example of such transformations. In the popular and travel literature, Mediterranean landscapes are often described as timeless. However, the rocky crags, steep-sided barrancos and stony expanses of desert are largely a product of human land use interacting with surface water. A Mediterranean traveller transported back in time to the Early Holocene might not recognize the densely wooded hills mantled with deep soils, broad valleys with shallow, perennial streams and the expanses of grassland that once typified this region. To understand the changes wrought by humans and water, we cannot depend solely on studies of the modern world, but need a time depth of centuries to millennia.

The related fields of archaeology, geomorphology and palaeoecology provide our best opportunities for identifying the long-term interactions of humans and water, and their long-term consequences. But if we hope to apply insights from past SESs to issues of human–water interactions today, we must move beyond the ways in which these fields are traditionally practised. The archaeological (and palaeoecological) record provides at best a few tiny windows on comparatively vast landscapes. Archaeological data—proxy data—are fragmentary, often indirect, inconsistently preserved and only partially recovered residues that we attempt to link inferentially with human behaviours. After over 150 years of scientific archaeology, we still debate the behavioural meanings for much of this record. Moreover, archaeological materials are static and no longer function within living human systems. Our attempts to *reconstruct* dynamic pre-historic SESs that varied across space and time are usually inductively derived stories that attempt to fill in with narrative the enormous gaps in our data. It is unsurprising, given the sparse and often ambiguous nature of the archaeological record, that very different narratives can be constructed to connect the dots between the same data points—regardless of how carefully and critically we make the complex chains of inferences needed for reconstruction. These narratives of the past are useful for some purposes, including as cautionary tales about human–environmental interactions (and, of course, also can be entertaining!). But in most cases, the archaeological (and palaeoecological) record is inadequate to serve as a reliable basis for inductive reconstructions of the past—especially reconstructions at the level of spatial/temporal resolution needed to help us better understand the operation and dynamics of SESs. While archaeological data collection techniques have improved significantly in many ways, there is nothing we can do to improve the quality of the archaeological record.

On the other hand, the archaeological (and palaeoecological) record has the potential to serve very well for *testing* models of complex SESs. When our models are narratives, inductively composed from the data used to test them, we face significant issues of circularity and of how to evaluate the results of such ‘tests’. However, advances in computational modelling offer the exciting possibility of constructing functioning, realistically abstract replicas of parts of dynamic SESs in a laboratory setting. That is, all models are abstractions and, in fact, we often learn more from carefully constructed abstractions based on explicit theoretical frameworks than from simply duplicating the real world in all of its detail. Such ‘abstract’ computational models are independent of the data used to test them. However, when they are parametrized with carefully collected, empirical data, such as ethnographically documented decision rules or the physical properties of water flowing across the landscape, they can be

evaluated more transparently and quantitatively against empirical data from the archaeological record than is possible with narratives. Finally, because they can be treated as controlled experiments rather than stories, computational models can be systematically and explicitly varied to better understand which cluster of organizational, interactional and initial parameters produce results that most closely fit the empirical record. This does not guarantee that models so constructed are true matches for past realities. However, this protocol much more tightly constrains the number of credible accounts possible and makes comparisons between alternative models of past SESs more feasible. Most importantly, by providing a means to create much more testable, and hence more reliable, models of SESs, this approach offers a way for the past to provide more robust guidance for current and future decision making.

A research programme, enhanced through computational modelling as described above, represents a fundamental change in the way archaeology (and related historical sciences) has been practised since its inception. Currently, regardless of the programmatic literature, most archaeology follows a well-established protocol: collect data from the archaeological record (usually through excavation of a small portion of a site), inferentially assign behavioural meanings to those data, inductively reconstruct aspects of past societies on the basis of the behavioural inferences and (in the more sophisticated research) use those reconstructions to make statements about past human societies and their changes, or even make statements about human societies more broadly. We suggest that archaeologists would be well served to adopt an alternative research program in which theory-driven models of human systems (including, but not limited to, SESs) are translated into dynamic computational models that produce measurable outcomes and those outcomes are tested against the empirical data of the archaeological record. This would build on the detailed knowledge and sophisticated methodological protocols that archaeologists have painstakingly acquired over the past century and a half, and at the same time would transform archaeology from a discipline focused exclusively on the past to a science of human dynamics—especially long-term human dynamics—with an incredibly rich and unique database with which to test and improve models of human systems whose value could extend far beyond our field.

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