Journal of Archaeological Science 39 (2012) 2908–2920

Contents lists available at SciVerse ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Don't abhor your neighbor for he is a pastoralist: the GIS-based modeling of the past human–environment interactions and landscape changes in the Wadi el-Hasa, west-central Jordan

Bülent Arıkan*

Research Center for Anatolian Civilizations, Koç University, İstiklal Caddesi No: 181 Merkez Han, Beyoğlu, Istanbul 34433, Turkey

ARTICLE INFO

Article history:
Received 19 September 2011
Received in revised form
10 April 2012
Accepted 14 April 2012

Keywords:
GRASS
Landscape modeling
Anthropogenic impacts
Extensive agropastoralism

ABSTRACT

Recently developed modules in GRASS GIS combine a wide variety of spatial data such as climatic, geological, and cultural in order to estimate how long-term interactions among these factors contribute to the evolution of natural environment and anthropogenic landscapes. Additionally, these modules allow users to visualize anthropogenic impacts of extensive agropastoralism on landscapes by subjecting the pre-defined catchment areas to repeated land use activities. The results emphasize the economic and ecological value of extensive agropastoralism in the marginal landscapes, which make anthropogenic activities more sustainable in the long-term. The results of this research are not only significant for its methodological contributions in anthropological archaeology but also have broader significance for researchers interested in interdisciplinary approaches in assessing the long-term dynamics of human-environment relations.

"*The only thing new in this world is the history that you don't know.*" Harry S. Truman, 33rd President of the United States of America (1884–1972).

1. Introduction

The continuing scholarly debates about global climate change along with current political and economic discussions about the massive scale and wide variety of anthropogenic impacts on the ecosystem have amplified interest in human-environment interactions. Archaeology has a significant role in interdisciplinary research projects since it integrates diverse analytical methods with broad intellectual background to contextualize complex human adaptive behavior at large spatio-temporal scales (van der Leeuw, 2000; van der Leeuw and Redman, 2002; Fisher and Feinman, 2005). Archaeologists can build theoretical frameworks to assess how past human behaviors and decision-making processes changed over time by combining both archaeological and environmental data. These frameworks are then used to assess the impacts of land use and resource procurement patterns in the context of past human-environment dynamics in addition to a more comprehensive evaluation of the emergence and evolution of socioecological systems.

Paleoenvironmental reconstructions have been the essential method of such projects (van der Leeuw, 1998; Peeples et al., 2006; Barton et al., 2010a,b) to illustrate the multi-dimensional, dynamic aspects of human–environment relationships that also contribute to changes in the political and economic organization of societies at large temporal scale. Besides laying out both the intended and unintended consequences of anthropogenic activities (e.g., deforestation, erosion, salinization), the study of past human impacts have the potential to shape the current and the future policies in order to: (1) create a more sustainable human–environment relationship, and (2) prevent major environmental catastrophes due to anthropogenic impacts, which would directly affect the survival of civilizations. The Central Arizona-Phoenix Long-term Ecological Research Project is an example of how the interdisciplinary researches on the past land use practices and decisions can be used to shape the current and future policies related to environment (also see Shrestha et al., 2012).

In this article, I focus on two related questions about reconstructing past environmental changes and human-environment interactions in the context of marginal landscapes of the southern Levant: (1) what are the impacts of changing climatic conditions towards hyper-aridity after 4400 BP on the environment, based on long-term variations in the rates of sediment erosion-deposition, and (2) what are the impacts of anthropogenic activities (i.e., extensive

---

* Tel.: +90 212 393 6101.
E-mail address: bulent.arikan@gmail.com.

0305-4403/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jas.2012.04.051

agriculture and pastoralism) on the succession rates and patterns of land cover in the arid zones of the southern Levant, and how such land use patterns contributed to long-term changes in landscape as result of varying types and intensity of human activities.

This research presents a new analytical tool for studying the impacts of both natural changes and human impacts on landscapes combining archaeological data, between the Chalcolithic and the Iron Ages (ca. 6500–2500 BP) from the semi-desert Wadi el-Hasa (Hasa hereafter) drainage in west-central Jordan (see Section 2.3), and the output of the Macrophysical Climate Modeling (MCM hereafter, see Section 3.1). Although the discussion is centered on the early metal ages of the southern Levantine drylands, the method of computational modeling for long-term landscape changes can be replicated in other regions, as long as crucial climatic and geological variables are known with some level of accuracy (see Section 3 for detailed discussion). On the other hand, the reader should refer to Bryson and DeWall (2007), Barton et al. (2010a,b), and Ullah (2011) for more information about the geoscientific aspects of the geographical information systems (GIS hereafter) methods used since the discussion is not focusing on these topics. The readers are encouraged to compare the results from Ullah (2011) and this research as the former uses the same methods of computational modeling in the Wadi Ziqlab of northern Jordan, which has different climatic and land cover characteristics than the Hasa.

2. The environmental and cultural background

2.1. The paleoenvironment of the Levant

In the discussions of prehistoric economic organization and ancient human impacts on environment, paleoenvironment stands out as the natural context of adaptive behaviors. In archaeology, there wide variety of methods that reconstruct prehistoric climate and environment using proxy data. Only when the archaeological evidence is combined with such reconstructions, it is possible to illustrate the dynamic relationship between the culture, its environment, and anthropogenic impacts on environments through time. The Levant has a long history of paleoenvironmental research using speleothems (Bar-Matthews et al., 1999), paleogeomorphology (Mabry, 1992), and paleolimnology (Frumkin, 1997; Bowman, 1997).

Palynology contributes to the study of past climates in a more indirect way: the assessment of climatic conditions through the reconstructed plant communities and their known environmental requirements. Although there are numerous case studies that cover hundreds of thousands of years of the environmental history, the most relevant examples related to the drought in the early metal ages will be used here. The first palynological research that provide evidence for late third millennium B.C. climatic oscillations, which may have contributed to the collapse of the Early Bronze II–III urban system in the Early Bronze IV in the Near East, comes from Horowitz's (1971, 1974) cores from Hula (K-Jam, U.P. 6 and U.P. 15) and Kinneret (D-1016/2) basins. In a more recent study of the pollen cores from the west side of the Jordan Rift Valley, Horowitz identifies a zone (i.e., Q-10: 11 Kyr to present) where a warm, dry interval roughly corresponds to the Early Bronze IV (Horowitz, 2001: 612).

Baruch's research is significant since the data bear the earliest signs of anthropogenic impacts (i.e., of especially horticulture and grazing) on the environment during the late Neolithic, which gradually intensify through the Chalcolithic and the Early Bronze, and eventually lead to the degradation of forests (Baruch, 1989: 292). This contributes to severe erosion due to cultivation, grazing and burning especially during the third and second millennia B. C.

Hunt et al. (2007) combine palynological data with geomorphology and geoarchaeology in order to illustrate the scale and the extent of climate change during the Holocene between the hyper-arid Wadi Arabah and the Mediterranean woodland in the uplands of Edom. Although the main focus of authors is on the environmental impacts of mining and smelting copper ores in the region, their discussion provides important clues about how intensive use of resources changed the landscape along with natural, climate-driven changes in the environment (Hunt et al., 2007: 1329–1330). Considering the long-term patterns in the vegetation history, Hunt et al. suggest that climate between the early and middle Holocene is wetter, which then turns arid in the Early Bronze Age (2007: 1332). These changes in vegetation from the early to the middle Holocene are well documented in other regions of the Near East and seem to have contributed to the emergence of a completely different landscape (i.e., incised wadi floors) and biota (i.e., steppe, desert) (Hunt et al., 2007: 1332).

Finally, Neumann et al. (2010) focus on a 75 km long transect along the western Dead Sea shore to study the palynological and sedimentological data in order to provide a detailed outline for the climatic fluctuations for the last 3500 years, using the vegetation history. Using the results from six cores, the researchers argue that the drop in the lake level and the low percentage of arboreal pollens during the Late Bronze Age indicate arid climate patterns, which last through the Iron age in the region (Neumann et al., 2010: 760–761).

2.2. The environment of the Hasa

The Hasa (Fig. 1) is the southernmost fluvial system in Jordan that drains into the Dead Sea, carving its way through marls and limestone rocks of the Upper (western terminus) Hasa to the Lower (eastern terminus) Hasa where talus deposits and extensive alluvial terraces have been identified (Schuldenrein and Clark, 1994, 2003). The drainage, which has highly dissected and varied topography, is bounded by the Arabian Desert on the east. The Karak Plateau, a geologically more stable region with thicker soil profiles and higher precipitation is to the north and the Edom Plateau is to the south of the Hasa (Fig. 2).

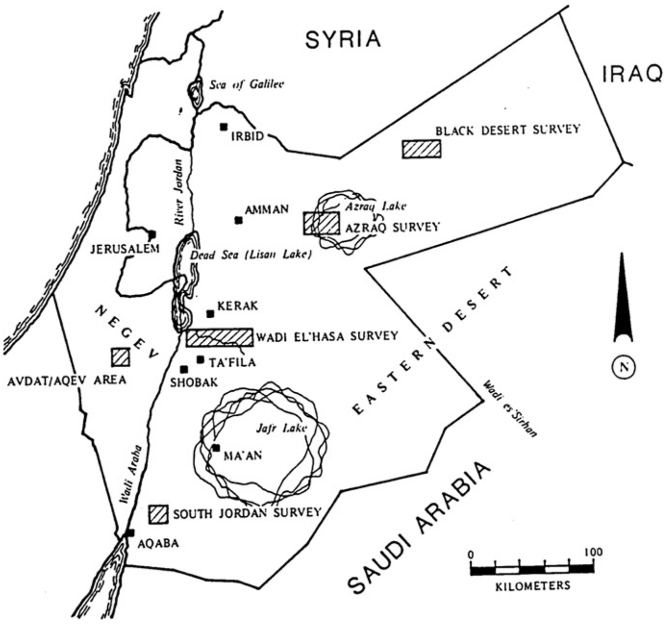

Fig. 1. The map of the Hashemite Kingdom of Jordan showing the location of the Wadi el-Hasa in relation to Amman, the Dead Sea and the Gulf of Aqaba (with permission, from Clark, 1998: 78).

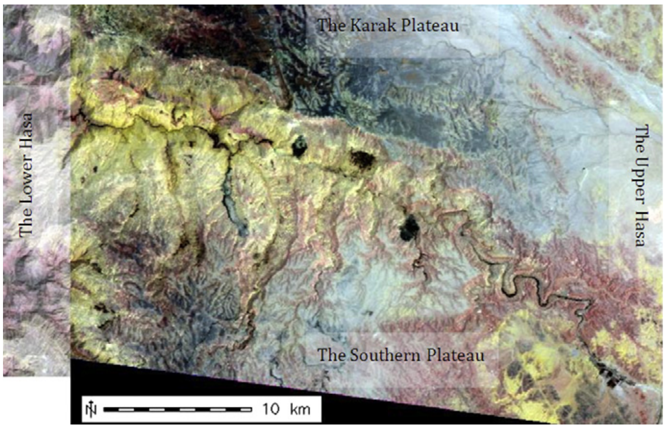

Fig. 2. TERRA ASTER imagery of the Wadi el-Hasa. The NW terminus is the Dead Sea, the drainage is between the Karak (due north) and the Edom (due south) plateaus.

Within the Hasa drainage, which covers approximately 972 square kilometers, the variation in annual precipitation amount ranges from 300 to 600 mm/year (Hill, 2006: 8). Irano-Turanian steppe climate is observed in the Hasa due to arid conditions that result from high summer evapotranspiration and extreme differences between daytime and nighttime temperatures (Hill, 2006: 8). Consequently, the land cover in the Hasa is composed of shrubs and grassland, which is analogous to the African Sahel. On the other hand, patchy distribution of the Mediterranean flora is observed along numerous springs and the wadi bed (Schuldenrein and Clark, 2003: 1–3). Due to these environmental attributes of the Hasa, the drainage can be said to represent a marginal landscape for human settlement.

2.3. The Archaeology of the Hasa

The cultural history of the Hasa has been well studied as result of the comprehensive field surveys of MacDonald (1988) and Clark (Coinman, 1998, 2000) that documented more than 2000 sites ranging from the Palaeolithic (ca. 80,000 BP) to the late Ottoman (ca. 1900) periods. Hill (2002, 2006) provides a detailed survey of the temporal changes in the settlement systems of the Hasa in relation to changes in environment and geology throughout the Holocene. Under the warmer and wetter conditions during the first half of the Holocene, settlements spread from the Upper to the Lower Hasa by the Chalcolithic and the Early Bronze Age I–III, ca. 6500–4400 BP (Hill, 2006; Arıkan, 2010).

With the onset of arid climate by the Early Bronze IV (ca. 4400 BP), the Hasa experienced a major abandonment of the region that lasted throughout the Middle and Late Bronze Ages (ca. 4000 and 3200 BP). Although hyper-aridity continued, the settlement activities of the Iron Age (ca. 2900 BP) showed intensification, which can be attributed to the rise of territorial kingdoms in the region (Arıkan, 2010). Under such climatic conditions, the subsistence patterns of societies in the southern Levant require greater attention since land use patterns directly impact the landscape and contribute to its long-term change.

Although agricultural and pastoral (i.e., animal husbandry) modes of subsistence complement each other for dietary requirements, there have been regional variations in the Near East for the socio-economic and political significance of each mode (Arıkan, 2011). Ancient Mesopotamian societies practiced intensive agropastoralism (Bar-Yosef and Meadow, 1995; Harris, 1996): clusters of dense population farming to obtain harvest several times in a year, which contributed to hierarchical political organization. The environmental aspects (i.e., climate, land cover, perennial fluvial systems) of this region made such activities possible, although they were environmentally exhaustive in the long-term. The exception to intensive agropastoralism in this region was southern Syria where the Syrian Desert made transhumant pastoralism (i.e., vertical seasonal movements on the landscape) more economically feasible.

Unlike their counterparts on the well-irrigated plains of Mesopotamia, the southern Levantine societies had low population density (i.e., small, scattered settlements) due to the environmental and climatic factors (LaBianca, 1990; Chesson, 2003; Arıkan, 2010). Extensive nomadic pastoralism (i.e., horizontal seasonal movements) emerged as the predominant subsistence system, and extensive agricultural production took place on the small patches near seasonal streams along wadi beds (LaBianca, 1990; Hill, 2006; Arıkan, 2011), which also played a part in the emergence of tribal heterarchic social organization. In this socio-economic context, it is possible to use geological, environmental, and cultural variables in order to accurately estimate how natural and anthropogenic factors played a role in the modification of the Hasa landscape during four millennia (6500–2500 BP).

3. Research methods

The GIS modules used in this research have been developed for the Geographic Resources Analysis Support System (GRASS GIS, GRASS hereafter) by the Mediterranean Landscape Dynamics Project (MEDLAND, http://www.asu.edu/clas/shesc/projects/medland/) under the directorship of C. Michael Barton at Arizona State University.

GRASS is a GIS platform with highly advanced topographic analyses and modeling modules (see Neteler and Mitasova, 2008 for a detailed background on the development of GRASS). Besides numerous raster-based spatial analyses scripts that are standard in GRASS package, MEDLAND (Mayer and Sarjoughian, 2007) developed several custom scripts to model the impacts of not only the changing environmental conditions on landscapes but also to assess long term anthropogenic land use (Barton et al., 2010a,b). These scripts employ critical geological, climatic, and cultural variables in modeling landscape changes such as slope of terrain, hardness of substratum, land cover, population density, size of catchment areas in addition to statistically retrodicted figures for precipitation, temperature, and evaporation through MCM.

3.1. High resolution, site specific, Macrophysical Climate Modeling (MCM)

MCM is a heat-budget approach (i.e., the relation between fluxes of heat into and out of a given region and the heat stored by the systems) to accurately identify the mean centers of high and low sea-level pressure systems that determine the weather and wind patterns at mid-latitudes along with Jet Stream and Intertropical Convergence (e.g., the boundary between the northern and southern hemisphere surface air) (Barry and Carleton, 2001: Bryson and DeWall, 2007). Using Bryson's MCM, it is possible to mathematically estimate meteorological parameters for as early as 40,000 BP, at 100-year intervals on the basis of meteorological data between 1960 and 1990 from weather stations around the target region (Bryson and DeWall, 2007).

The results of the MCM at individual weather station around the target region have been extended over continuous landscapes by regression modeling, hence creating precipitation landscapes in the GIS platform (Figs. 3 and 4) (Barton et al., 2010a,b). The MCM analysis relies on four weather stations around the Hasa to collect and regress data into the past. In order to maintain consistency in

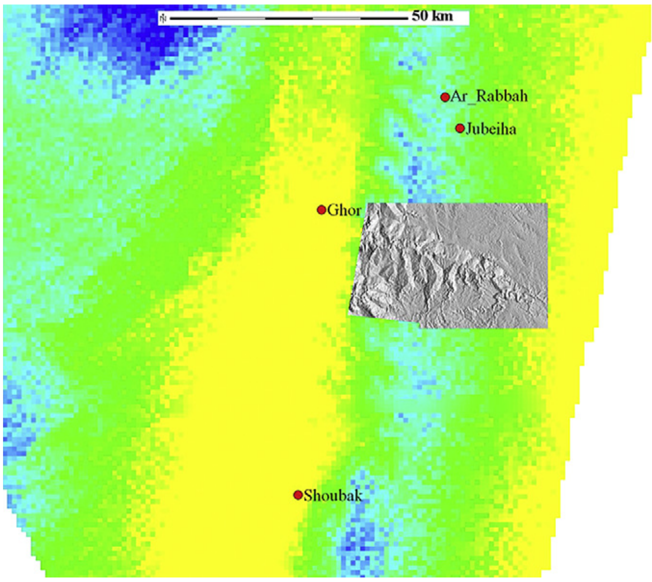

Fig. 3. The map of the weather stations around the Hasa, which are used for the Macrophysical climate Modeling. The base map is the precipitation landscape of the southern Levant for 1000 BP and the location of the Hasa is shown by a shaded relief map.

the data, the climatic variables used in this particular modeling of the Hasa landscape are taken from Ar-Rabbah station (see Fig. 3).

3.2. The landscape evolution

The term "landscape evolution" refers to multifaceted and long-term transformations that occur in the environment solely as result of natural factors. The script 'r.landscape.evol', developed by the MEDLAND Project for GRASS, uses variables such as rainfall (R-factor), soil erodibility (K-factor), land cover (C-factor), stream transport type (i.e., how much bedload is carried by river) and efficiency (i.e., the capacity of a river to suspend sediment), slope of the terrain, as well as the output from MCM like the amount of precipitation per rainy day and the number of days of rain per year (i.e., the ratio of the average precipitation amount to the precipitation per rainy day) (Table 1) (Barton et al., 2010a,b) in order to model their combined impact on the landscape. All these variables factor in the landscape change, especially under hyper-arid environmental conditions, where sudden storms can lead to severe erosion, changes in hydrology, and surface dynamics.

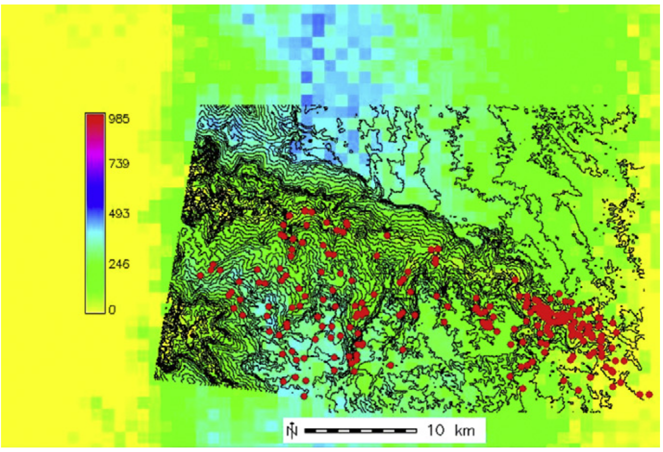

Fig. 4. The precipitation landscape map of the southern Jordan for 1000 BP, including the Hasa (shown as 50-m contour map) and the early metal age sites. The legend shows precipitation in milimeters. The differences in precipitation from north to south and west to east are clearly visible in the map.

The script uses a bedrock elevation map (i.e., a raster map showing the elevational differences in bedrocks within the target area) and a soil depth map (i.e., a raster map showing which parts of the landscape have thickest layers of soil) in order to calculate and display cumulative and annual changes in erosion-deposition, elevation, and soil depth in output raster maps for time intervals specified in the analysis. Both of these maps are derived from modern DEMs. It should be noted that any kind of map is an approximation. In this case, the modern DEM is not reflective of the ancient conditions but it is an approximation. The bedrock and soil depth maps are intended to inform the user about the basic geology of the region to be modeled. The elevational differences within the region displayed in the bedrock map are important as hillslope erosion deposition (HED) affects flat areas minimally. The soil depth map on the other hand, shows locales in the region where the soil depth is the thickest. Such thick layers of soil then point the parts of the region that have been affected from HED through time. Therefore, these maps are used as certain benchmarks in calculating net erosion-deposition rates. On the other hand, the ideal source for such approximations of ancient topography would be a "PaleoDEM" (Barton et al., in press), which relies on detailed georcheological data from a region in order to reconstruct ancient topography by erasing recent changes, such as channeling. Although there had been considerable geoarchaeological research in the Hasa (Schuldenrein and Clark, 1994, 2001, 2003), the drainage is too big to make an attempt to prepare a Paleo DEM with the existing body of geoarcheological data.

A research of this scale will take years of sustained geo-archaeological investigations in the region. Given the resources at my disposal, I decided to use the modern DEM of the Hasa to prepare the bedrock map, which is smoothed intentionally during spatial interpolation in order to mimic the characteristics of the ancient topography, using geoarchaeological data available from the Hasa.

The soils depth map used in the landscape evolution module is used to understand where in the Hasa the sediment is eroded and redeposited. Such calculations are based on empirical research (Heimsath et al., in press) relating topographic curvatures to depth of soil. Consequently, the soil map not only provides the landscape evolution script some sediment to erode and redeposit but more importantly using this map as a proxy, the module accurately calculates the locales of net erosion and redeposition in the research area. This method provides a better estimation of soil depth in a region than simply mantling an even layer of soil over all areas.

The output raster maps of the landscape evolution module can be queried to display sediment erosion-deposition values at any specific location on the landscape. Additionally, the cumulative erosion-deposition map (i.e., the "difference map") can also be prepared by subtracting the modern DEM of the region from the DEM of the final model year. These individual and cumulative erosion-deposition maps are then used to assess the role and contribution of natural factors in changes in the landscape in the Hasa region.

3.3. Anthropogenic impacts on the landscape

The MEDLAND Project developed an additional script, 'r.agropast.extensive', which analyzes, quantifies, and maps anthropogenic

Table 1
The summary table showing the climatic and environmental variables used for landscape evolution modeling in the Hasa. The average precipitation is the mean value for each period, calculated from precipitation landscapes. R-factor refers to the rainfall index, which is calculated by the Macrophysical climate model for each century and the average for each period is used here. K-factor refers to the soil erodibility, which is a set value that changes from one landscape to another. C-factor denotes the land cover where shrubs, the common vegetation in the Hasa, have the lowest value.

Period	Average precipitation (mm)	Number of rainy days	R-factor	K-factor	C-factor	Soil density	Number of years
Chalcolithic	462	78	4.450	0.42	0.01	1.2184	900
EB I–III	434	78	4.457	0.42	0.01	1.2184	1100
EB IV	405	74	4.444	0.42	0.01	1.2184	300
M-LB	372	70	4.455	0.42	0.01	1.2184	900
IA	339	66	4.475	0.42	0.01	1.2184	400

impacts on landscapes as reflected in changes in the composition and density of land cover classes (Ullah, 2011: 625–626). Combined with the landscape evolution modeling described in the previous section, these two modules allow researchers to prepare long-term models of landscape evolution using the main drivers of change in the environment: the climate and the anthropogenic activities. However, the modeling of the latter depends on identifying the land cover classes in the study area, which can be done with the multispectral analysis of LANDSAT images (Ullah, 2011: 625), as well as defining the catchment areas. The "catchment area" is the hotspot on the landscape where human actions related to agriculture and herding, in addition to habitation, take place. Such zones of anthropogenic impacts on the landscape emerge around settlements. Therefore, the modeling of human-induced landscape change should take place within these impact zones at desired temporal scale.

The extent of agropastoralist impact zone on the landscape needs to be defined using 'r.catchment', which is another MEDLAND Project script that takes a point (i.e., an archaeological site such as a farm or a village) on the landscape and creates agricultural and pastoral catchments around sites (Ullah, 2011: 628–629). In calculating the pastoral catchment area, since sheep and goats tend to graze at locales far from habitation areas, the size of the catchment area is usually kept large, at approximately 10 square kilometers (pastoral catchment = 10,000,000 square meters). This represents a distance that shepherds can comfortably cover in one day based on calorie expense, their ability and decisions to move on terrain (Coppolillo, 2000: Ullah, 2011). Based on low population densities in the Hasa during the early metal ages, the land use models estimate that herds in the Hasa used about 50% of land available around a site for grazing (Table 2) leaving the rest for agricultural and settlement activities.

Empirical data are needed about population size at each site in order to accurately calculate the agricultural catchment areas since the size of fields would depend on the population at a site. Based on the ethnoarchaeological research in the Near East, farmers need roughly 1.36 ha (ha.) of fields per person (Zorn, 1994). Using the number of habitation units at a site and multiplying this number by five – the projected number of people living at each habitation unit – (Zorn, 1994), a population estimate for each site can be reached. Based on the population estimate for the site, the size of the agricultural catchment can be calculated using 1.36 as the coefficient.

Table 2
The summary table showing the number of habitation units, estimated population, coefficient for population and site size for each site used in modeling.

Site	Habitation units	Population	Per person area (ha)	Site area (ha)
WHS 23	18	90	1.36	122.4
WHS 165	2	10	1.36	13.6
WHS 615	8	40	1.36	54.4
WHNBS 216	2	10	1.36	13.6

The fallow period, an amount of time when a plot of land is not used for agriculture in order to allow for regeneration of nutrients in the soil, is another factor that needs to be considered in calculating the size of the agricultural catchments. Depending on the amount of land left for fallow, the agricultural impact zone may grow significantly. In the models presented here, 20% fallow is allowed: a relatively low percentage since families farmed for self-subsistence in the Hasa, which did not put as much pressure on the land as intensive production systems did. This means that each farmer needs additional land every fifth year for farming. Therefore, the agricultural catchment must be five times larger. The size of the agricultural catchment then has to be multiplied by five (Table 3). The agricultural catchment calculations also need to consider the degree of slope of the terrain. In the models presented here, the agricultural catchments exclude terrains that have slopes greater than 20° as the early metal age settlement density of the Hasa sharply drops when this threshold is exceeded (Arıkan, 2010). In this case, the Model goes on with calculations until the specified catchment size is reached after excluding the steep slope terrain.

Secondly, land cover classes need to be defined, which will be used in modeling the impacts of extensive agricultural and pastoral land use patterns (for the definition of extensive agropastoralism, see Section 2.3). Since this module simulates the land use practices of agropastoralists and calculates the scale and the extent of anthropogenic disturbance on the land cover around the site, the land cover classes need to accurately reflect the diversity and composition of the plant community as well as the succession patterns of that specific vegetation (i.e., what kinds of plants may be observed in patches under human use once these spots are abandoned). When left alone, a cleared plot of land recover in 50 years (Barton et al., 2010a,b: 372). Considering the hyper-arid climate and predominance of desert-steppe vegetation in the Hasa, this succession pattern is assumed to start with bare land,

Table 3
The summary table showing the sizes of agricultural and pastoral catchments for each site used in modeling. For calculations of agricultural catchment area, sloping terrains of 20° or higher are excluded around each site. Terrains steeper than 20° are rarely used for farming in the Hasa however steepness is not an issue for pastoral land use.

Site	Slope threshold (degrees)	Agricultural catchment (ha) for 20% farming	Pastoral catchment (ha) for 50%
WHS 23	20	647.1	970
WHS 165	20	73.3	1046
WHS 615	20	282.5	1017
WHNBS 216	20	67.4	1092

gradually change into grasslands, and finally transform into a composition of grass and small trees, which reflects the characteristic range of vegetation in this type of climate zone. These constitute the land cover classes used for models presented here. The cover-management (C-) factor values associated with these classes are: 0.1 for the bare land, 0.005 for grassland, and 0.009 for grass with small trees. These thresholds indicate that the risk of erosion is much higher for bare land and it gradually decreases as land cover evolves into grassland first, and then into grass with small trees.

Finally, there is enough input data to run the land use model. The script calculates human impacts in both the pastoral and agricultural zones concurrently, therefore the user may provide both catchment maps as input. Additionally, the user has to provide the rules and color files for land cover and C-factor so that GRASS assigns specific colors to groups of vegetation. Once the number of model years is specified, the module is ready to process the data and create output maps for agricultural and pastoral impacts.

4. The research results

4.1. The landscape evolution

It is important to note that erosion is not just a direct result of how much water is in the system. Although aridity causes channel cutting, which consequently increases erosion, other significant factors that increase the rate of soil displacement are the type and density of human activity. The events of erosion-deposition are highly complex and they result from an intricate combination of natural and anthropogenic factors. The latter group of factors is not considered in this model since the input data strictly are about climate, hydrology, and geology. Therefore, the temporal patterns of erosion-deposition summarized below should be treated with caution.

The results of the Model can most efficiently be presented as a “difference map” (Fig. 5) as explained in Section 3.2. The difference map contains cells that have negative (i.e., erosion) or positive (i.e., deposition) values, mapping the exact locales of erosion-deposition on the landscape. However, before moving into the discussion of temporal erosion-deposition patterns, it is important to look at the environmental variables used in the modeling of landscape evolution for the early metal ages of the Hasa in Table 1.

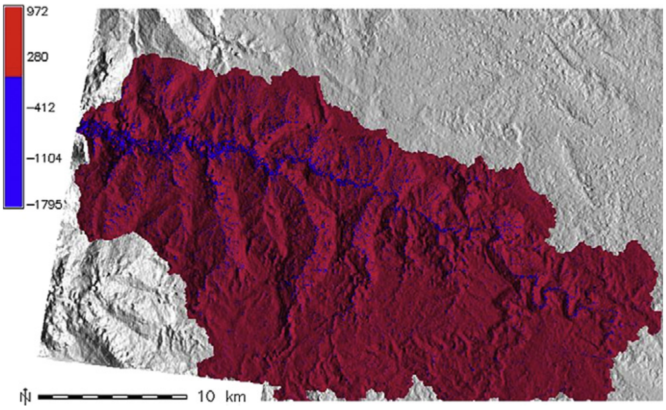

Fig. 5. The cumulative elevation change map. This map is the result of operation (the modern DEM – the elevation map of the last IA iteration). The results suggest that erosion takes place across the drainage, especially along the Hasa main channel between the central and west Hasa. The major erosional activity takes place in the western terminus of the Hasa while the upper Hasa experiences minimal erosion. The legend shows the amount of sediment eroded or deposited in each cell.

The second and the third columns in Table 1 show changes in precipitation between the Chalcolithic and Iron Ages. The results of MCM suggest that there is 123 mm of deficiency in average precipitation from the start of the Model to its end, which shows progressive aridity in the region. A further support to increased drought comes from the statistic of the number of rainy days in the drainage: the Iron Age experienced 12 days of less rain compared to the Chalcolithic period. These changes suggest that although the actual amount of precipitation does not change much, it may be significant in pushing the semi-desert environment into hyper-arid. The fewer number of rainy days means that the Iron Age rainfall has torrential nature: the rain events not only become episodic and hard to predict but more importantly the amount of rainfall per rain event can be overwhelmingly high for arid environment to tolerate. Such events become the norm starting with the Early Bronze IV in the Hasa and these events significantly increase erosion-deposition rates. The nature of rainfall (i.e., patterned vs. torrential) is the biggest contrast between the first (i.e., Chalcolithic-Early Bronze III) and the second (i.e., Early Bronze IV-Iron Age) halves of the early metal ages. The change in the mean soil depth supports this argument: between the Early Bronze IV and the late Iron Age the increase in the mean soil depth is noteworthy in light of such events.

The statistics about mean erosion, deposition, and soil depth at the end of the model run for each cultural period are shown in Table 4. The Early Bronze IV witnesses the highest rates of erosion in the Hasa. The model shows that erosion takes place along the main Hasa channel at varying intensity while the majority of erosional activity is in the lower Hasa (i.e., As-Safi) and central drainages, which contributes to the current dissected topography and exposes alluvial terraces. Considering the facts that climate turns arid and the precipitation regime changes in this period, this outcome of the Model is expected: the Hasa river is cutting its channel around As-Safi, where it is below the sea level due to dropping water table. The Early Bronze IV also has the highest rate of mean deposition, which can be attributed to changing precipitation regime as discussed above. As the rain events become torrential in nature, their capacity to carry sediment increases, which is accurately predicted in the model. These results suggest that the Early Bronze IV represents the period when the Hasa landscape is rapidly and significantly changing. These results become more striking when it is considered that these calculations do not take anthropogenic activities into account.

The Chalcolithic period ranks second in terms of mean erosion values. The model suggests that the heavily eroded part of the Hasa is between the central drainage and the lower Hasa, which has the steepest slopes and less stable soil cover. The upper Hasa does not show significant erosional activity. This is expected since this area has relative geomorphic stability, which is also implicated by dense Chalcolithic settlement activity.

Table 4
The summary table showing the statistical results of landscape evolution models by period. The highest value in each column is shown in bold.

Period	Mean erosion	Mean deposition	Mean soil depth
Chalcolithic	−0.00077	0.0020	1.350
EB I–III	−0.00074	0.0021	1.835
EB IV	**−0.00099**	**0.0036**	1.944
M-LB	−0.00068	0.0020	2.266
IA	−0.00056	0.0019	**2.389**

The Early Bronze I–III ranks third with relatively lower erosion/deposition rates. Although significant erosion activity continues in the As-Safi area, low-density erosion is observed in the central parts of the main Hasa channel. The upper Hasa remains stable without any significant sign of erosion. When compared to the second half of the early metal ages, both Chalcolithic and the Early Bronze I–III show higher rates of erosion, except for the Early Bronze IV. The Chalcolithic period represents warmer and wetter climatic phase whereas the climate of the Early Bronze I–III shows initial signs of aridification. However, the difference between these periods in terms of the amount of precipitation is negligible and the modeling duration is only slightly longer in the Early Bronze I–III. Therefore, it is possible to suggest that anthropogenic activities that gained intensity during the Early Bronze I–III may be responsible for slight decline in erosion and significant increase in soil depth. In other words, human activities cannot be said to have a negative impact on the environment of the Hasa.

The Middle and Late Bronze rates of erosion/deposition are among the lowest. Based on the figures from Table 4, it is clear that the Early Bronze IV represents a phase when both erosion and deposition reach the peak and starting with the Middle Bronze, these rates drop. The Model results suggest that soil loss starts to affect the upper Hasa, although major erosion is taking place in the western terminus. Since the Hasa drainage is almost completely abandoned with the exception of few small settlements, the level of anthropogenic activities is negligible in this period. Consequently, it is possible that the hydrology of the drainage is slowly adapting to the new, arid climate regime. This gradual reaction is possibly reflected in slightly declining values for erosion and deposition.

The Iron Age has the lowest mean erosion value in Table 4. Although the results of MCM suggest that the drought reached its peak and the precipitation regime already changed by the Iron Age, the duration of the model is significantly short and the results do not consider anthropogenic activities. The model results for the Iron Age reiterate the pattern of the previous periods: the most significant erosion takes place between the central part of the drainage and the lower Hasa while erosive activity is much less significant in the eastern half of the drainage or in the tributary valleys. On the other hand, archaeological data illustrate that the Iron Age is the most densely settled period among the early metal ages (Hill, 2006; Arıkan, 2010).

The Iron Age settlement patterns and land use practices have been discussed elsewhere (Arıkan, 2010, 2011) however, it is important to note that larger settlements and clusters of small sites always preferred geologically stable parts of the drainages such as the southern plateaus and the upper Hasa. Such preferential settlement of landforms and extensive pastoralism of the Iron Age can be viewed as a mechanism of minimizing environmental risks. This aspect of anthropogenic activities can also be illustrated by comparing the pre-drought and post-drought mean soil depth. Between the Chalcolithic and the Early Bronze IV, the mean soil depth increased about 594 mm, whereas it is 445 mm for the period between Early Bronze IV and the Iron Age. Although torrential precipitation regime may be responsible for slightly higher rate of soil deposition, it is noticeable that dense settlement activity and increased land use do not cause significant soil loss in the Hasa drainage that has gradually become a hyper-arid environment by the end of the Iron Age.

4.2. Anthropogenic impacts

In order to present a more complete assessment of the landscape evolution, anthropogenic activities and their impacts on the landscape also need to be quantified at different spatio-temporal scales. In this section, I present the results of analyses from the extensive agropastoral land use model, which focuses on how the composition of land cover changes after set number of years of agropastoral land use in the marginal Hasa landscape.

For the modeling, I use four sites (Fig. 6), which are representative of the early metal age Hasa settlements in terms of variations in occupational history, function, and size. The features at these sites have been mapped both on-site and using aerial photos. Table 5 provides information about the estimated population and size of agricultural, pastoral catchment sizes for each site. WHS 23 and WHS 615 are the two largest sites that are located on plateaus. The hamlets are in valleys near the main Hasa channel (WHS 165), and in the upper Hasa (WHNBS 216).

The model is run for 50 years at each site mainly because the settlements have short occupational histories due to the environmental and socio-economic conditions discussed in Section 2.2. However, the site of WHNBS 216 is subjected to long-term (i.e., 200 years) modeling in an attempt to simulate what the scale and the extent of anthropogenic impacts on the landscape around a site would have been in the long-term. Such land use analyses on GIS platforms inherently produce numerous maps and in order to keep the discussion concise, I present maps and summarize the model results from two of the sites: a village (WHS 23) and a hamlet (WHNBS 216). However, a comprehensive discussion on the general results of modeling is provided in section 4.3. Fig. 7 through 12 are maps at 10-m resolution: each pixel represents 100 square meters on the ground however, the pixels may look large or small depending on the scale of each map, which is determined by the size of the site and its catchment area.

4.2.1. WHS 23

The site, which is located on the southern plateau of the west Hasa, is one of the few villages from the early metal ages. Fig. 7 shows that a village of this size needs 12 ha of arable land and 627.5 ha of land is in fallow at the end of 50 years of extensive agricultural land use. The legend shows land cover classes at the end of the final iteration, where moderately sparse grassland becomes widespread at the site. Fig. 8 on the other hand, shows the impacts of 50-year long extensive pastoral land use: grassland and small trees constitute the majority of vegetation.

4.2.2. WHNBS 216

The results of 50-year long extensive agriculture (Fig. 9) and pastoral (Fig. 10) land use at this hamlet in the east Hasa are more

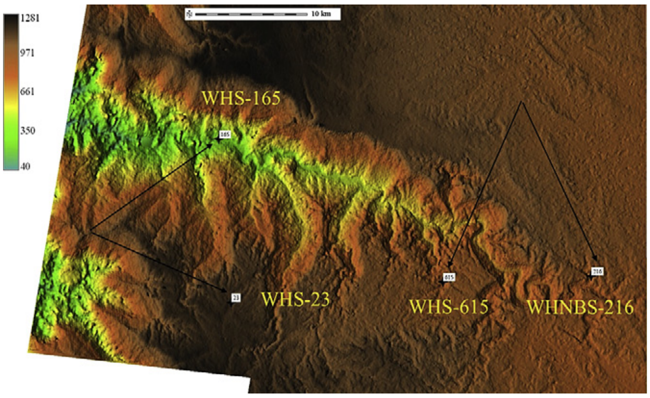

Fig. 6. The Hasa sites used for extensive agropastoral land use modeling shown on the shaded relief map of the drainage. The selection of the sites reflects the diversity of land forms that Hasa sites show: plateaus, valleys and ridges.

Table 5
The summary table showing the number of habitation units, estimated population, coefficient for population, site size, the sizes of agricultural and pastoral catchments for each site used in modeling. For calculations of agricultural catchment area, sloping terrains of 20° or higher are excluded around each site. Terrains steeper than 20° are rarely used for farming however steepness is not an issue for pastoral land use.

Site	WHS 23	WHS 165	WHS 615	WHNBS 216
Habitation units	18	2	8	2
Population	90	10	40	10
Per person area (ha)	1.36	1.36	1.36	1.36
Site area (ha)	122.4	13.6	54.4	13.6
Slope threshold (degrees)	20	20	20	20
Agricultural catchment (ha) for 20% farming	647.1	73.3	282.5	67.4
Pastoral catchment (ha) for 50%	970	1046	1017	1092

informative since the cultural landscape of the early metal age Hasa is dotted with many small settlements like hamlets, farmsteads, and domestic clusters, which were inhabited by a household. Fig. 9 shows that the hamlet needs 1.5 ha of arable land and 65 ha of land is in fallow at the end of the final iteration, where extensive agriculture initiates moderately sparse grassland around the site. Fig. 10 shows that extensive pastoral land use leads to grassland with small trees around the settlement.

The results of the long-term anthropogenic impacts on the land cover around the hamlet are shown in Figs. 11 and 12. Fig. 11 shows that at the end of the final iteration, 64.7 ha of land is in fallow and the long-term extensive agriculture does not create significantly different land cover than the short-term. On the other hand, the long-term extensive pastoralism at the site (Fig. 12) leads to different land cover: 200-year long pastoral land use initiates grassland and shrubs, which has lower C-factor value in comparison with grassland and small tress that result from short-term pastoral land use. This implies that long-term pastoralism increases the risk for human-induced erosion and land degradation.

4.3. The impacts of extensive agropastoral land use on the Hasa environment

Following the brief, site-specific overview of anthropogenic impacts above, I present a comparative assessment of the impacts of extensive agropastoral land use in the Hasa in this section. The area of each land cover type resulting from the Model at sites is subjected to *t*-test in order to explore whether the differences in sizes of land cover classes at sites are statistically significant. *T*-tests do not show statistically significant variations in the data. On the other hand, I use the coefficient of variation (CV), which is the ratio of the standard deviation to the mean to explore if there are patterned variations. CV is normalized measure of variation, which is independent of the units of observation and it allows cross-comparison between data sets where standard deviation can be greater. Hence, CV is a more reliable measure of the magnitude of variation among data sets. Plotting the median CV values for the area of each land cover class shows subtle differences among sites.

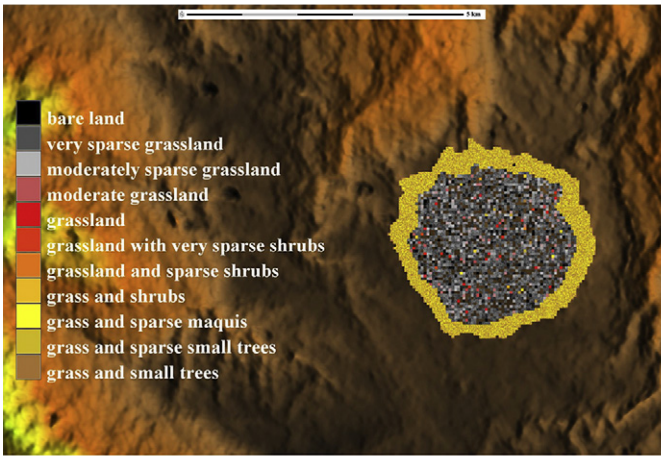

Fig. 8. The map showing the primary land cover classes at WHS-23 after 50 years of extensive pastoral land use. The legend from Fig. 7 applies to the red-gray section at the center of the image. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.3.1. The impacts of extensive agropastoral land use on the biodiversity and environmental stability

The percentage of land cover classes represented at sites after extensive agricultural land use models (Fig. 13) show that four land cover categories persist regardless of the size, function, locale of sites. The most heavily represented land cover classes are very sparse and sparse grasslands. Temporal aspect does not factor in these patterns. However, the longer lands remain under extensive agriculture, the smaller areas of bare land they have.

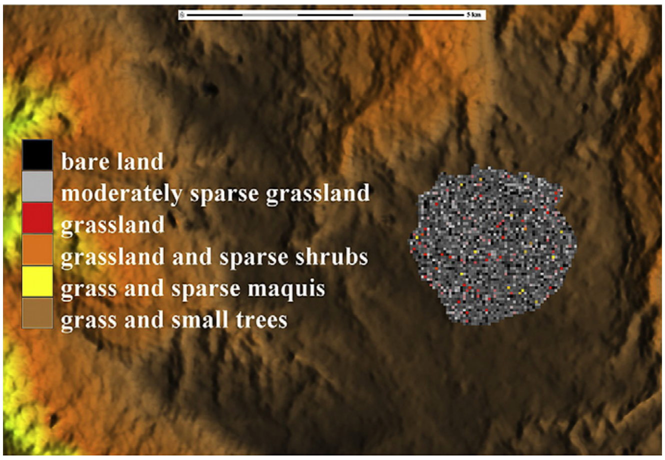

Fig. 7. The map showing the primary land cover classes at WHS-23 after 50 years of extensive agricultural land use.

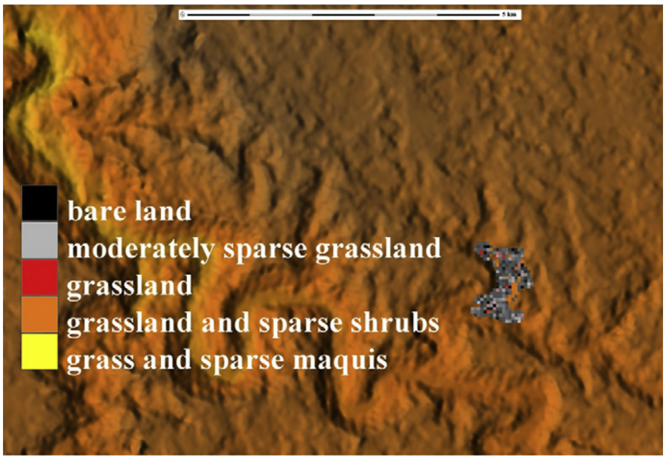

Fig. 9. The map showing land cover classes at WHNBS-216 after 50 years of extensive agricultural land use.

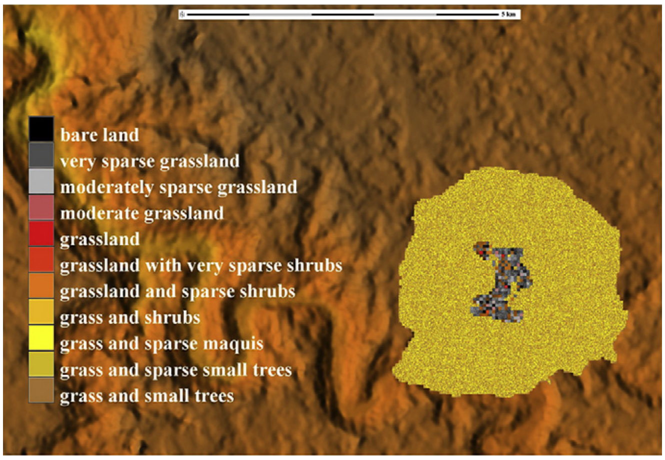

Fig. 10. The map showing land cover classes at WHNBS-216, after 50 years of extensive pastoral land use. The legend from Fig. 9 applies to the red-gray section at the center of the image. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

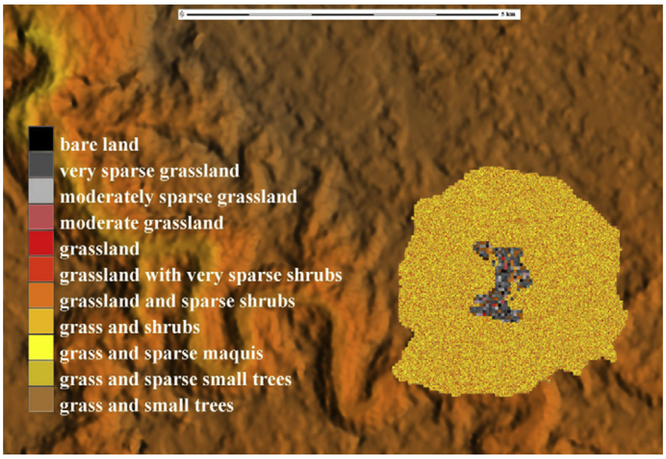

Fig. 12. The map showing land cover classes at the site after 200 years of pastoral land use. The legend from Fig. 11 applies to the red-gray section at the center of the image. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

A comparison of the results above with the results of the extensive pastoral land use model reveals some interesting patterns. Fig. 14 shows the percentages of the main land cover classes resulting from such modes of subsistence. There are seven categories represented, which suggests that pastoral activities not only have economic significance in marginal lands such as the Hasa (Section 2.3), but more importantly they provide ecological benefits by increasing biodiversity. Although keeping plant diversity at the lowest level is a basic strategy in agriculture, increased biodiversity as a result of pastoralism has significant implications for the ecology of drylands.

Unlike extensive agriculture, site size seems to play a role in the diversity of land cover composition in extensive pastoral land use. After 50 years of modeling, the largest sites (WHS-23 and WHS-615) have higher percentages for very sparse grassland and sparse grassland, which contrasts with the grass and small trees type of vegetation at smaller sites (WHS-165 and WHNBS-216). The relatively low percentage of small trees or maquis around large sites may be a factor of their size and population, which translates into denser population of livestock at large sites.

While site location does not seem to make difference, temporal scale introduces another dimension regarding the anthropogenic impacts of extensive pastoralism in the Hasa. As discussed in Section 4.2.2, the comparison of 50-year and 200-year land use models at WHNBS-216 suggest that the latter temporal scale of land use may result in grassland and shrubs. This kind of land cover has lower C-factor value than grassland and small trees, which is the end result of the shorter land use model. Consequently, it is possible to suggest that long-term pastoralism, even at extensive mode, causes sufficient land cover change that may increase the risk of erosion uniformly, regardless of landform, size, or location of sites in the drainage. These changes directly affect the environmental stability of the marginal lands where such critical balances can easily be upset. The short occupational history of the early metal age Hasa sites can then be considered as an effort to alleviate the unintended consequences of anthropogenic activities. Based on the C-factor values, the best land cover type to resist erosion in the Hasa is grassland with small trees, which persists in the area after short-term extensive agropastoral land use.

Fig. 11. The map showing land cover classes at the site after 200 years of extensive agricultural land use.

4.3.2. The site-based comparisons of the extensive agropastoral land use modeling

The land use models provide statistics about the area of individual land cover classes for each model year, which can be quantified to measure the scale and the extent of human impacts on vegetation at each site. In order to make comparisons across land cover classes visually less challenging, I grouped 50 land cover classes under 12 categories.

The plotting of the median CV values across these categories is shown in Fig. 15. Although the patterns emerge at each site is close to one another (and, therefore *t*-tests fail to show statistical significance for one site), there is recognizable variation among the sites. With the exception of the long-term model at WHNBS-216, sites in Fig. 15 show that model results are comparable for the land cover classes at both ends of the spectrum. This is expected since sites start and end with specific classes of vegetation. However, differences emerge at the center of the spectrum, which point to variations in the way the succession takes place. In other words, each site has slightly different pattern from the rest in terms of reaching to the final point. As the two largest sites (WHS-23 and WHS-615) show almost identical pattern of land cover succession from moderately sparse grassland to grass and shrubs, hamlets (WHS-165 and WHNBS-216) show widely dispersed pattern, which is especially noticeable in the peak of WHS-165 for grassland with

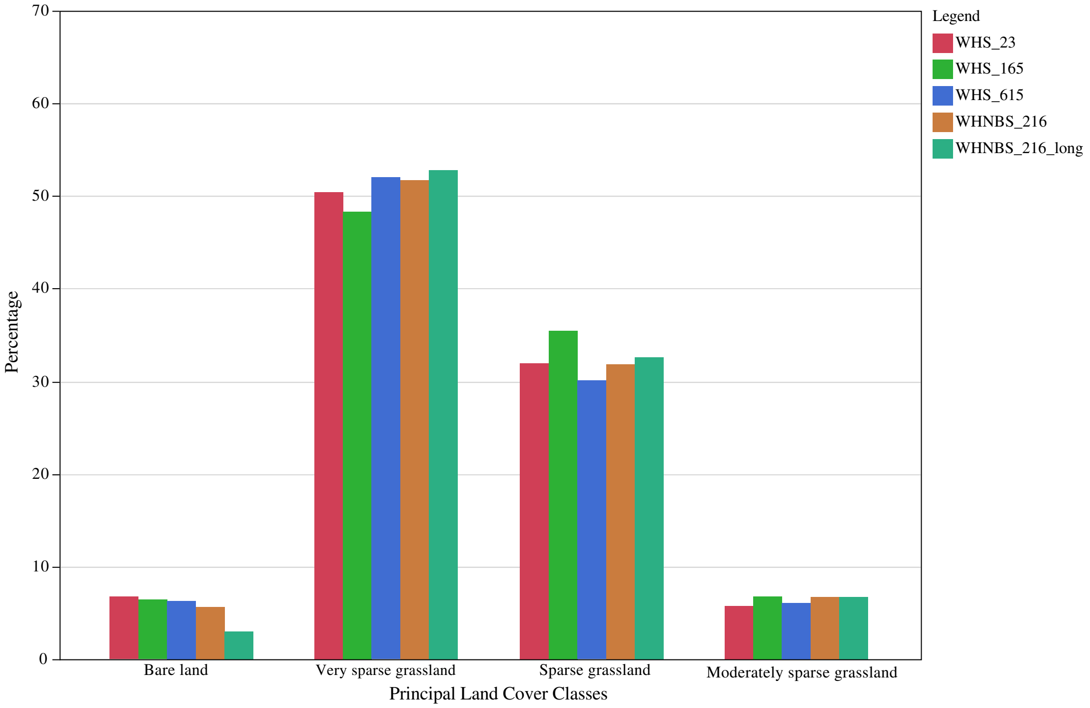

Fig. 13. The bar chart comparing the percentages of principal land cover classes after extensive agricultural land use in the Hasa. The *y*-axis shows percentages of each land cover class at sites modeled. The sites are color-coded (see the legend), which are arranged from the west to the east. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

very sparse shrubs. Such spikes suggest that small settlements, like hamlets, show greater annual variation in land cover: high CV values indicate that the area of a vegetation class changes significantly through time. On the other hand, the long-term land use model at WHNBS-216 reveals an opposite trend: low CV values suggest that the land cover classes in this model remain stable (for a comparison, see Barton et al., 2010a,b: 374, 378). This pattern is the direct result of the temporal length of the model. The long-term model results show that as the duration of extensive agropastoral land use increases (50-years vs. 200 years), the benefits (i.e., increased risk of erosion) diminish, as discussed above.

The results of extensive agropastoralist land use model applied to a diverse group of early metal age sites in the Hasa show that the site size and the length of anthropogenic activities are important factors in the scale and the extent of changes in land cover in the marginal landscapes. Although the differences in land cover classes are subtle and the diversity of vegetation is significantly low under extensive agricultural land use (Fig. 13), major changes in the vegetation around a site is brought by extensive pastoralist land use (Fig. 14). The modern day “patchiness” of vegetation in the drainage agrees well with the results of the land use models above.

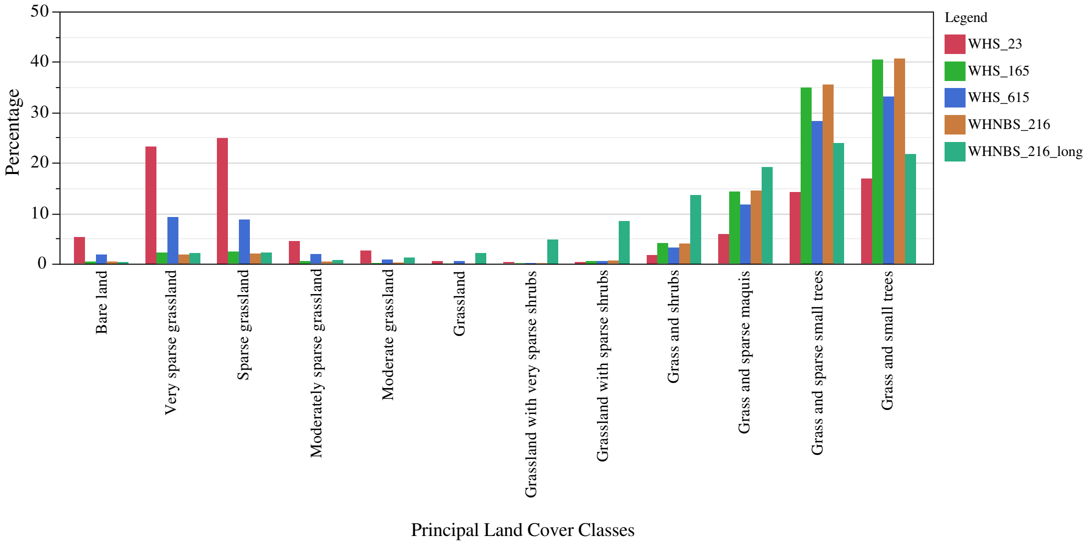

Fig. 14. The bar chart comparing the percentages of principal land cover classes after extensive pastoral land use in the Hasa. The *y*-axis shows percentages of each land cover class at sites modeled. The sites are color-coded (see the legend), which are arranged from the west to the east. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

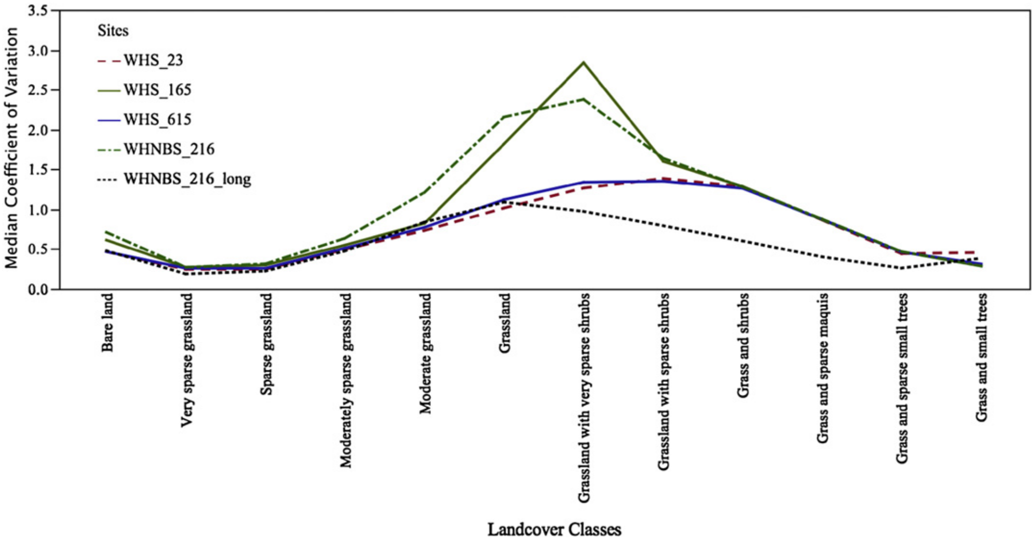

Fig. 15. The line chart showing the coefficient of variation values for each principal land cover class according to land use models applied at sites.

5. Overview, conclusion, and broader impacts

5.1. Overview

This research focused on the impact of both the changing environmental conditions and the anthropogenic activities on the marginal Hasa landscape through GIS-based spatio-temporal modeling that used several key natural and cultural variables. The results of the landscape evolution models suggest that considerable erosion takes place along the main Hasa channel between As-Safi and the central portion from 4400 BP to 3200 BP, which agrees well with the results of MCM that show change in the precipitation regime towards infrequent and torrential rainfall after 4400 BP.

The modeling of human impacts for extensive agropastoral land use reveals different trends and informs us about the relationship between biodiversity, environmental stability, and the type of anthropogenic disturbance in marginal lands. The results of extensive agropastoral land use models suggest that the ecological benefits may diminish swiftly when the sites in marginal environments like the Hasa, exceed a threshold between 54 and 122 ha (i.e., WHS-615 and WHS-23) for agriculture or practice pastoralism in the long-term (Table 5, Figs. 14 and 15).

5.2. Conclusion

The land use models presented in this research provide important clues about the history of the multi-dimensional human–environment relations. Although the land use models discussed here are mainly attempts to portray the scale and the extent of human impacts under certain scenarios, such as the type and the length of land use, the predictive models are becoming more accurate as the body of environmental and cultural data grow as well as the algorithms for the scripts are updated frequently to account for complex and multifaceted human–environment interactions. Consequently, the results of this research should be taken as suggestions: while the models can predict the direction and the intensity of human impacts on environments, the results do not reflect the reality. On the other hand, integrating wide variety of data in GIS-based modeling and the interpretation of the results allow researchers to approach human decision-making from theoretical perspectives. Scholars of the ancient Mesopotamia (Marfoe, 1979; LaBianca, 1990; Chesson, 2003) have frequently stated that extensive land use systems, especially nomadic pastoralism, have been the trademark of tribal social systems that usually occupy environmentally marginal lands. These views not only emphasized the biological needs for pastoralism that provided the much needed source of protein following the transition to food-producing economies, but they also asserted the view that extensive land use patterns suited well to the resilient aspect of tribes, who survived under harsh climatic conditions by maintaining their flexible social and economic organization that allowed them to respond to major perturbations such as drought and erosion (LaBianca, 1990; Arıkan n.d.).

Recently, ethnography-oriented research on nomadic pastoralism has been diversified with quantitative and hypothesis-driven studies. Alvard and Kuznar (2001) use the ethnographic data on the decisions to hunt versus domesticate prey among the Piro people in the Peruvian Amazon. Using the data from the Paleolithic–Neolithic transition in the Old World, they built a model on these parameters for explaining how animal husbandry might have emerged from the perspective of behavioral ecology (Alvard and Kuznar, 2001: 300–301). According to this model, the diminishing availability of prey made conservation necessary for the growing human population around ca. 10,000 BC (Alvard and Kuznar 2001: 301). Following the sedentarization of groups, animals with small body size (e.g., sheep, goats) became the focus of attention for domestication since they have higher reproduction rates and they can be kept in high density (Alvard and Kuznar, 2001: 301–302). The results of Alvard and Kuznar can then be used to argue that the pastoral mode of subsistence also allows for surplus production: a surplus on the hooves.

The land use models discussed in this article takes such quantitative research on the significance of a certain kind type of subsistence strategy and tests that economic behavior in terms of its actual impacts on the environment. These tests reveal that the early metal age inhabitants of the Hasa, who were already practicing extensive agropastoralism for several environmental and socio-economic reasons mentioned above, also mitigated the increased risk of erosion due to agriculture by combining it with pastoralism. Consequently, this mode of land use enabled them to forge a subsistence pattern that was more sustainable in terms of environmental impacts, if kept at smaller scale and pursued in short-term.

The type, intensity, and the duration of anthropogenic disturbance are important factors that determine whether resource procurement methods are sustainable or causing environmental degradation (i.e., overexploitation, loss of natural function). The land use models illustrate that the extensive agropastoralism had been the most efficient method of keeping human impacts within manageable limits and increasing biodiversity while mainly introducing maquis and small trees that consequently reduce the risk of erosion. This subsistence pattern lays the foundation for dimorphic social organization in the region (Marfoe, 1979; Arıkan, 2010), bringing flexibility and resiliency against environmental stress.

5.3. *Broader impacts*

This research directly contributes to the study of anthropological archaeology, climate change, and anthropogenic impacts on the dry lands of the eastern Mediterranean. The research methodology and types of data used in this article enable the researchers to: (1) observe the diversity of human responses in wide topographic and climatic settings, hence to test the resiliency of societies from both social and economical perspectives, which are inherently reflected in settlement systems and land use patterns in a region, (2) examine spatio-temporal patterns in the rate and extent of changes in the land cover as climatic and anthropogenic factors are combined to assess impacts on the geology and land cover, and (3) test theoretical frameworks about the emergence of various social organization types (i.e., hierarchy vs. heterarchy) from the perspective of economic and environmental sustainability.

This study also contributes to a new area of interdisciplinary research where scholars are interested in understanding complex systemic interrelationships among social systems and ecosystems. This has recently led to the emergence of the term ‘human socioecosystems’. In this new approach, the aim is to understand how humans adapt to certain environmental conditions, what the nature and the extent of each relationship with the ecosystem is, and more importantly how intended and unintended consequences of these interactions play out in the long-term. The researchers are equally interested in conceptualizing the society as a dynamic system that changes as results of such interactions. Additionally, for scholars with parallel interests, my research is more important for its methodology. The analyses of data from diverse sources are usually done with the GIS, whose greatest capability is mapping the results, showing the relationships at both spatial and temporal dimensions. In that respect, not only the utilization of the MEDLAND scripts but also the logic behind them are expected to enable researchers to explore how processes bring change in dynamic and complex human–environment relationships, which are timeless concepts that affect societies throughout the world.

Acknowledgements

I am grateful for the financial support of the Kress Foundation as well as the hospitality and support of the American Center of Oriental research in Amman. I am also indebted to the General Directorate of Antiquities of Jordan for their cooperation. The Graduate College at Arizona State University generously supported me during the final stages of my dissertation research. I am grateful for the supervision, continuous support, guidance, and collegiality of my advisor, Prof. C. Michael Barton, during both my doctoral education and postdoctoral research at Arizona State University. Without his encouragement, I would not be able to acquire the skills I developed. Last but not least, I am indebted to my friend Isaac Ullah, not only for sharing his work but also for eagerly spending his valuable time and energy in answering my questions about GRASS as well as sharing his research that amounted to the preparation of these scripts.

References

Alvard, M.S., Kuznar, L., 2001. Deferred harvests: the transition from hunting to animal husbandry. American Anthropologist 103 (2), 295–311.

Arıkan, B., 2010. Reorganization and risk: environmental change and tribal land use in marginal landscapes of southern Jordan. Unpublished Ph.D. dissertation, School of Human Evolution and Social Change, Arizona State University.

Arıkan, B., 2011. Cooperation and competition: the comparative assessment of tribal dynamics in the marginal landscapes of the Wadi el-Hasa, in west-central Jordan in the Early Bronze and Iron ages. Traces in Time 1. http://www.archaeologicaltraces.org/OJS/index.php/traces_in_time/article/view/4/22.

Arıkan, B., n.d. Villages in the desert? A theory-oriented discussion on the emergence of social complexity among the Iron Age tribes of the eastern Mediterranean.

Barry, G., Carleton, A.M., 2001. Synoptic and Dynamic Climatology. Routledge, London.

Barton, C.M., Ullah, I., Bergin, S., 2010a. Land use, water and Mediterranean landscapes: modelling long-terms dynamics of complex socio-ecological systems. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 368 (1931), 5275–5297.

Barton, C.M., Ullah, I., Mitasova, H., 2010b. Computational modeling and Neolithic socioecological dynamics: a case study from Southwest Asia. American Antiquity 75 (2), 364–386. doi:10.1016/j.ecomodel.2012.02.010.

Barton, C.M., et al. Looking for the future in the past: long-term change in socioecological systems. Ecological Modeling., in press.

Baruch, U., 1989. Palynological evidence of human impact on the vegetation as Recorded in late Holocene Lake sediments in Israel. In: Bottema, S., Entjes-Nieborg, G., van Zeist, W. (Eds.), Man's Role in the Shaping of the Eastern Mediterranean Landscape. Balkema, Rotterdam, pp. 283–293.

Bowman, D., 1997. Geomorphology of the Dead Sea western Margin. In: Niemi, M.T., Ben-Avraham, Z., Gat, J.R. (Eds.), The Dead Sea. The Lake and Its Settings. Oxford University Press, Oxford, pp. 217–225.

Bryson, R.A., DeWall, K. McEnaney (Eds.), 2007. A Paleoclimatology Workbook: High Resolution, Site-Specific, Macrophysical Climate Modeling. The Mammoth Site, Hot Springs.

Bar-Matthews, M., et al., 1999. The Eastern Mediterranean paleoclimate as a reflection of regional events: Soreq cave, Israel. Earth and Planetary Science Letters 166, 85–95.

Bar-Yosef, O., Meadow, R.H., 1995. The origins of agriculture in the Near East. In: Price, T.D., Gebauer, A.B. (Eds.), Last Hunters and First Farmers. New Perspectives on the Prehistoric Transition to Agriculture. School of American Research Advanced Seminar Series. School of American Research Press, Santa Fe, pp. 39–94.

Chesson, M.S., 2003. Households, houses, neighborhoods and corporate villages: modeling the Early Bronze Age as a house society. Journal of Mediterranean Archaeology 16 (1), 79–102.

Clark, G.A., 1998. The Negev Model for paleoclimatic change and human adaptation in the Levant and its relevance for the Paleolithic of the Wadi al-Hasa (west-central Jordan). In: Coinman, N.R. (Ed.), Surveys, Settlement Patterns and Paleoenvironments. Arizona State University, Tempe, pp. 77–97. Anthropological Research Papers No. 50.

Coinman, N.R. (Ed.), 1998. The Archaeology of the Wadi Al-Hasa, West-Central Jordan. Excavations at Middle, Upper and EpiPaleolithic Sites, vol. 2. Arizona State University, Tempe. Anthropological Research Papers No. 50.

Coinman, N.R. (Ed.), 2000. The Archaeology of the Wadi Al-Hasa, West-Central Jordan. Surveys, Settlement Patterns and Paleoenvironments, vol. 1. Arizona State University, Tempe. Anthropological Research Papers No. 52.

Coppolillo, P.B., 2000. The landscape ecology of pastoral herding: spatial analysis of land use and livestock production in east Africa. Human Ecology 4, 527–560.

Fisher, C.T., Feinman, G.M., 2005. Landscapes over time: resilience, degradation, and contemporary lessons. American Anthropologist 107 (1), 62–69.

Frumkin, A., 1997. The Holocene history of Dead Sea Levels. In: Niemi, M.T., Ben-Avraham, Z., Gat, J.R. (Eds.), The Dead Sea. The Lake and Its Settings. Oxford University Press, Oxford, pp. 237–248.

Harris, D.R., 1996. The origins and spread of agriculture and pastoralism in Eurasia: an overview. In: Harris, D.R. (Ed.), The Origins and Spread of Agriculture and Pastoralism in Eurasia. Routledge, London, pp. 552–573.

Heimsath, A.M., et al. Soil production limits and the transition to bedrock dominated landscapes. Nature Geoscience, in press.

Hill, J.B., 2002. Land-use and land abandonment in Wadi al-Hasa, west-central Jordan. Unpublished Ph.D. dissertation, Department of Anthropology, Arizona State University.

Hill, J.B., 2006. Human Ecology in the Wadi Al-Hasa. Land Use and Abandonment through the Holocene. University of Arizona Press, Tucson.

Horowitz, A., 1971. Climatic and vegetational developments in northeastern Israel during the Upper Pleistocene–Holocene times. Pollen et Spores 2, 255–278.

Horowitz, A., 1974. Preliminary palynological indications as to the climate of Israel during the last 6000 Years. Paleorient 2 (2), 407–414.

Horowitz, A., 2001. The Jordan Rift Valley. Balkema, Lisse.

Hunt, C.O., et al., 2007. An 8000-year history of landscape, climate, and copper exploitation in the Middle east: the Wadi Faynan and the wadi Dana National reserve in southern Jordan. Journal of Archaeological Science 34, 1306–1338.

LaBianca, S., 1990. Sedentarization and Nomadization: Food System Cycles at Hesban and Vicinity in Transjordan. Andrews University Press, Berrien Springs.

Mabry, J. B., 1992. Alluvial cycles and early agricultural settlement phases in the Jordan Valley. Ph.D. dissertation, Department of Anthropology, University of Arizona.

Marfoe, L., 1979. The integrative transformation: patterns of sociopolitical organization in southern Syria. Bulletin of the American School of Oriental Research 234, 1–42.

MacDonald, B., 1988. The Wadi El Hasa Archaeological Survey 1979–1983, West-Central Jordan. Wilfrid Laurier Press, Waterloo.

Mayer, G.R., Sarjoughian, H.S., 2007. Complexities of simulating a hybrid agent-based landscape model using multi-formalism composability. SpringSim 2, 161–168.

Neteler, M., Mitasova, H., 2008. Open Source GIS a GRASS GIS Approach, third ed. Springer, New York.

Neumann, F.H., et al., 2010. Vegetation history and climate fluctuations on a transect along the Dead Sea west shore and their impact on past societies over the last 3500 years. Journal of Arid Environments 74, 756–764.

Peeples, M., Barton, C.M., Schmich, S., 2006. Resilience lost: intersecting Landuse and landscape dynamics in the upland southwest. Ecology and Society 12 (22), 1–18.

Shrestha, M., et al., 2012. Land fragmentation due to rapid urbanization in the Phoenix Metropolitan area: analyzing the spatiotemporal patterns and drivers. Applied Geography 32, 522–531.

Schuldenrein, J., Clark, G.A., 1994. Landscape and prehistoric chronology of west-central Jordan. Geoarchaeology 9, 31–55.

Schuldenrein, J., Clark, G.A., 2001. Prehistoric landscapes and settlement geography along the Wadi Hasa, west-central Jordan 1: geoarchaeology, human paleo-ecology and ethnographic modeling. Environmental Archaeology 6, 25–40.

Schuldenrein, J., Clark, G.A., 2003. Prehistoric landscapes and settlement geography along the Wadi Hasa, west-central Jordan. Part II: towards a model of paleo-ecological settlement for the Wadi Hasa. Environmental Archaeology 8, 1–16.

Ullah, I.T., 2011. A GIS method for assessing the zone of human-environmental impact around archaeological sites: a test case from the late Neolithic of Wadi Ziqlâb, Jordan. Journal of Archaeological Science 38, 623–632.

van der Leeuw, S., 1998. The Archaeomedes Project – Understanding the Natural and Anthropogenic Causes of Land Degradation and Desertification in the Mediterranean. Office for Official Publications of the European Union, Luxembourg.

van der Leeuw, S., 2000. Land degradation as a socionatural process. In: McIntosh, J.A., Tainter, J.A., McIntosh, S.K. (Eds.), The Way the Wind Blows: Climate, History, and Human Action. Columbia University Press, New York, pp. 357–384.

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

Zorn, J.R., 1994. Estimating the population size of ancient settlements: methods, problems, solutions, and a case study. Bulletin of the American School of Research 295, 31–48.