Sediment Dynamics in Changing Environments (Proceedings of a symposium held in Christchurch, New Zealand, December 2008). IAHS Publ. 325, 2008.

Glacial–interglacial cycles, soil erosion and natural desertification in the Middle East

YOAV AVNI

Geological Survey of Israel, 30 Malkhe Yisrael St, Jerusalem 95501, Israel

yavni@gsi.gov.il

Abstract Field observations and luminescence dating indicate that, during the Late Pleistocene glacial period (OIS 4 and 3), deposition of fluvio-loess sediments, with minor erosion cycles, occurred in the arid and semi-arid regions of the Middle East. Severe erosion started during OIS 2 and continued into the Holocene. Since the mid-Holocene, the co-existence of soil and runoff created unique geomorphic conditions, which enabled the establishment of runoff-harvesting agricultural farms in the arid regions of the Middle East. This led to the redeposition of fine alluvial loess sediments originating from Late Pleistocene loess sections. This accumulation, which contributed to soil conservation, is not related to any apparent Late Holocene pluvial climatic phase. The human impact, contributing either to land degradation or to soil conservation, is super-imposed on the natural long-term trend of geomorphic change leading toward natural desertification. Similar processes are operating in other semi-arid regions worldwide.

Key words continental erosion; global climate change; geomorphic change; gully incision; desertification; loess sediments; Negev Highlands; Middle East

INTRODUCTION

Continental soil erosion and land degradation are a cause for increased concern around the world (UNCOD, 1977; UNCED, 1992; UNCCD, 1995). This problem becomes critical in the arid and semi-arid regions of the world (roughly 37% of the world land), as it greatly affects the agricultural potential and the lives of large populations in those regions (e.g. Mainguet, 1991; Bruins & Lithwick, 1998). Soil erosion is achieved by several mechanisms, such as gully, rill and sheet erosion, among which gully erosion was found to be the primary erosion agent within the drainage basins (Bull, 1997; Poesen *et al*., 2002, 2003; Valentin *et al*., 2005). This process is very active in the hilly and rocky areas of the arid and semi-arid regions of the Middle East, such as in southern Israel, northern Egypt and most of Jordan and Syria. In these regions the majority of the agriculture potential and the natural range biomass are concentrated in relatively narrow valleys, which are occasionally irrigated by desert floods. In recent times erosion processes have eroded the fine alluvial sediments (referred to here as re-deposited loess sediments) which were deposited along the valleys during past events (Avni, 2005; Avni *et al*., 2006). The powerful desert floods form gullies and headcuts within these valley floors, endangering the natural environment, human population and infrastructures (Avni, 2005; Avni *et al*., 2005; Valentin *et al*., 2005). Consequently, the natural biomass, the biodiversity and the agricultural potential are being severely reduced as a result of the concentration of the flood waters within narrow gullies, leading to a dramatic reduction of the irrigation efficiency. Similar processes of soil erosion and gullying are active in other semi-arid and arid regions worldwide. The wide range and distribution of soil erosion phenomena within the Middle East raises several questions regarding the soil erosion and gullying processes, such as the current and the long-term rates of the deterioration processes and the mechanism behind their initiation.

One of the main benefits of studying continental soil erosion in the Middle East region resulted from the rich historical and archeological documentation available in these regions. The ancient constructions provide a wide range of dated installations that can serve as benchmarks for approximate estimation of the total development of gullies and volume of soil erosion since historical times. Therefore, these regions provide perfect study areas, enabling documentation and comparison of changes in the volumes and rates of soil erosion over several time scales, from annual to millennial, and throughout most of the Holocene (Avni, 2005; Avni *et al*., 2006). Understanding the complex relations between the natural and anthropogenic causes of soil erosion and land degradation is of prime importance and is a necessary step toward developing modern strategies for soil conservation in arid zones around the world.

Soil erosion, gullying and natural desertification

Desertification is described as "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors including climatic variations and human activities" (UNCED, 1992). It is considered as the final result of complex processes that are generally attributed to human pressure on marginal lands (e.g. Bruins & Berliner, 1998; Mainguet & Le'tolle, 1998). Following this view, many studies attributed most of the land degradation and desertification processes to anthropogenic activities such as overgrazing, unsustainable agriculture activities and modern infrastructures (Mainguet, 1991; Bruins & Lithwick, 1998; Fanning, 1999; Poesen *et al*., 2002, 2003; Billi & Dramis, 2003; Vandekerckhove *et al*., 2003; Wu & Cheng, 2005; Jiongxin, 2006). Nonetheless, in many regions geological records show several natural Quaternary cycles of shifts from aggradation and deposition to land degradation and erosion, long before the anthropogenic impact started (e.g. Botha *et al*., 1994; Erikson *et al*. 2000; Clarke *et al*., 2003; Avni, 2005; Avni *et al*., 2006). These soil erosion processes, which occurred in natural environments and are not related to any anthropogenic intervention, generate a geomorphic change which leads toward land degradation, decreased natural biomass and reduction of the agricultural potential. These are clear indications for desertification processes, whose natural origin leads us to attribute the term "natural desertification" to this ongoing natural mechanism (Avni, 2005; Avni *et al*., 2006).

Natural desertification processes in the Negev Highlands

The Negev Highlands region in southern Israel is a typical arid, hilly terrain representing large areas in the Middle East (Fig. 1). It is characterized by a rocky terrain at an elevation of 600–1000 m, consisting of marine sediments – mainly limestone, dolomite, chalk, and chert layers of

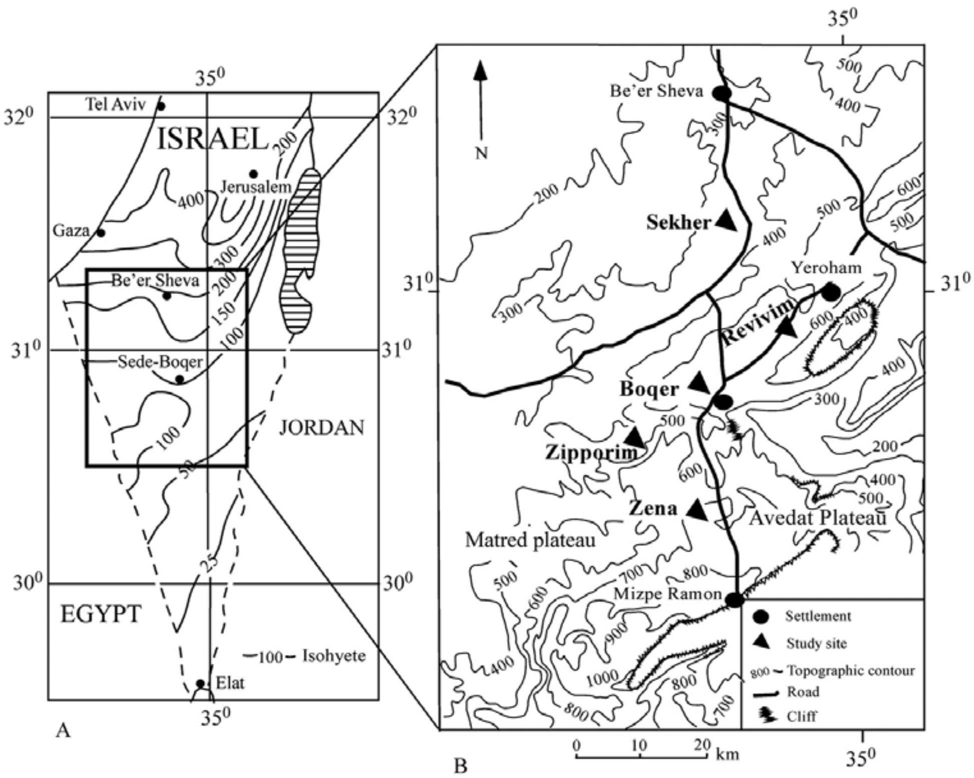

Fig. 1 (a) Location and rainfall distribution map of the Negev Highlands (after Evenari *et al*., 1982). (b) Topographic map of the Negev Highlands and the study sites (modified after Avni, 2005).

Fig. 2 The Boqer headcut in the Negev Highlands (for location see Fig. 1). Note the sharp drop in the vegetation cover below the headcut.

Upper Cretaceous to Tertiary age (Avni, 1991). Numerous streams flowing northwestward to the Mediterranean and northeastward to the Dead Sea basin dissect the area. The valleys are incised to depths of up to several tens of metres below the hills, and the valley floors are between 30 and 200 m wide. In most cases the valley bottoms are filled with Late Pleistocene sediments, mainly fluvial loess and gravel, deposited in the region during the last glacial interval, approximately 70–20 ka BP (Avni, 1991; Zilberman, 1992; Avni *et al*., 2006). During the Late Pleistocene glacial episodes, desert-loess transported by the wind from the northern margins of the Sahara Desert accumulated in the Negev, covering both hill slopes and valleys (Bowman *et al*., 1986; Yair, 1987). Under the current Holocene arid climate, an increase in the erosive processes, especially in gully formation and headcut migration upvalley, has been observed in the region (Fig. 2). The vegetation cover within the valleys varies from relatively dense coverage of desert shrubs and annuals above the headcut to almost no vegetation within the gully developed below the headcut. The headcuts and their related gullies are 3–4 m deep, forming vertical walls, which dissect the fine-grained alluvial fill of the valleys (Fig. 2). During flashflood events the gullies concentrate runoff into well-defined channels that incise the alluvial fill and restrict the floodwater available for vegetation on the rest of the valley floor. The present ongoing gullying process is causing intensive erosion of the valley soils, removing a major part of the Late Pleistocene sediments. Most of this activity is causing great damage to the ancient agricultural fields irrigated by runoff-harvesting techniques, constructed in the region during historical times (3000–1000 BP) (Evenari *et al*., 1982; Lender, 1990; Haiman, 1992).

METHODS

A regional field survey was carried out in 1990 in order to locate representative drainage basins and headcut sites for detailed study. Four drainage basins were selected: the Zipporim (where preliminary observations were initiated in 1984), Revivim, Boqer and Sekher basins, each representing a unique geomorphic configuration (Fig. 1). The mechanism and rate of gully retreat were studied in these basins over 17 years (1990–2007). The following methods were used in order to monitor the headward erosion and to determine its rate:

(1) At each site, several benchmark pins were installed around the major headcut and its gully walls, in order to establish long-term measurement of the gully configuration.

(2) The annual retreat rate and the total loss of soil were calculated by three-dimensional mapping of the headcut and are given in m^3 for each headcut site (Table 1). The accuracy is in the range

of ±10%. Adding the value of 1500 ± 250 kg/m^3 for loess sediments (Ninari and Berliner (2002), it became possible to estimate the soil erosion in terms of weight.

It is important to note that these calculated volumes does not represent the total soil erosion in the entire basin under study and does not include that of other soil erosion agents such as rill and sheet erosion. Therefore, these calculations are the minimum erosion estimations for each drainage basin.

(3) An archaeological survey was carried out in the Negev Highlands during the 80s and 90s of the last century (e.g. Lender, 1990; Haiman, 1992). The survey mapped the agricultural installations and facilities (such as stone dams, agricultural terraces and irrigation channels) and was used to assess the gully positions in historical times and their migration rates during the last few millennia.

(4) Approximately 70 OSL age determinations were elaborated during the present study by Dr. Naomi Porat of the Geological Survey of Israel, focusing on late Pleistocene and Holocene fluvial sediments. The methodology for the sampling and age analyses follows that presented in Avni *et al*. (2006).

Table 1 Comparison of gully head retreat and soil erosion in study sites, Negev Highlands.

Headcut site	A	B	C	D	E	F	G	H	I
Zipporim eastern	9	Chalk and loess	7.60	0.44					
Zipporim central	9	Loess	17.8	1.04					
Zipporim western	9	Loess and conglomerate	7.70	0.45					
Total for Zipporim	9		17.80	1.04	2000 3000$^{(*)}$	117 176.4$^{(*)}$	19.6	750	0.004
Revivim southern	15	Loess	27.1	1.6					
Revivim northern	15	Loess and conglomerate	7.2	0.45					
Total for Revivim	15		27.1	1.6	1000 1500$^{(*)}$	58.8 88.2$^{(*)}$	5.8	800	0.005
Boqer southern	100	Loess	49.9	3.11					
Boqer northern	100	Loess	45.2	2.82					
Total for Boqer	100	Loess	49.9	3.1	2000 3000$^{(*)}$	117.6 176.4$^{(*)}$	1.7	1000	0.006
Sekher southern	100	Sandy loess	196.2	17.8					
Sekher northern	100	Sandy loess	57.1	11.42					
Total for Sekher	100		250	16.6	9000 13500$^{(*)}$	600 900$^{(*)}$	9.6	8750	0.08

A, Catchment area upstream of headcut (km^2); B, Headcut composition; C, Total retreat 1990–2007 (m); D, Average annual retreat (m/year); E, Total eroded soil 1990–2007 (m^3), tons $^{(*)}$; F, Average annual eroded soil (m^3/year), tons/year $^{(*)}$; G, Average annual eroded soil (tons/km^2); H, Total area which lost agricultural and range potential 1990–2007 (m^2); I, Average annual rate of lost area (ha/year). $^{(*)}$ Calculation based on 1500 kg/m^3 (after Ninari & Berliner, 2002).

RESULT AND DISCUSSION

Recent monitoring

Headcut migration and gully development in the region and their influence on the desert ecosystem were studied between 1990 and 2007 in four representative drainage basins in the Negev Highlands region (Zipporim, Revivim, Boqer and Sekher, see Table 1, Figs 1, 2 and 3). The change in irrigation efficiency below the headcuts is reflected in a sharp estimated drop of 70–90% in the floral biomass, causing a reduction in the range value of 83–99%. During the monitoring

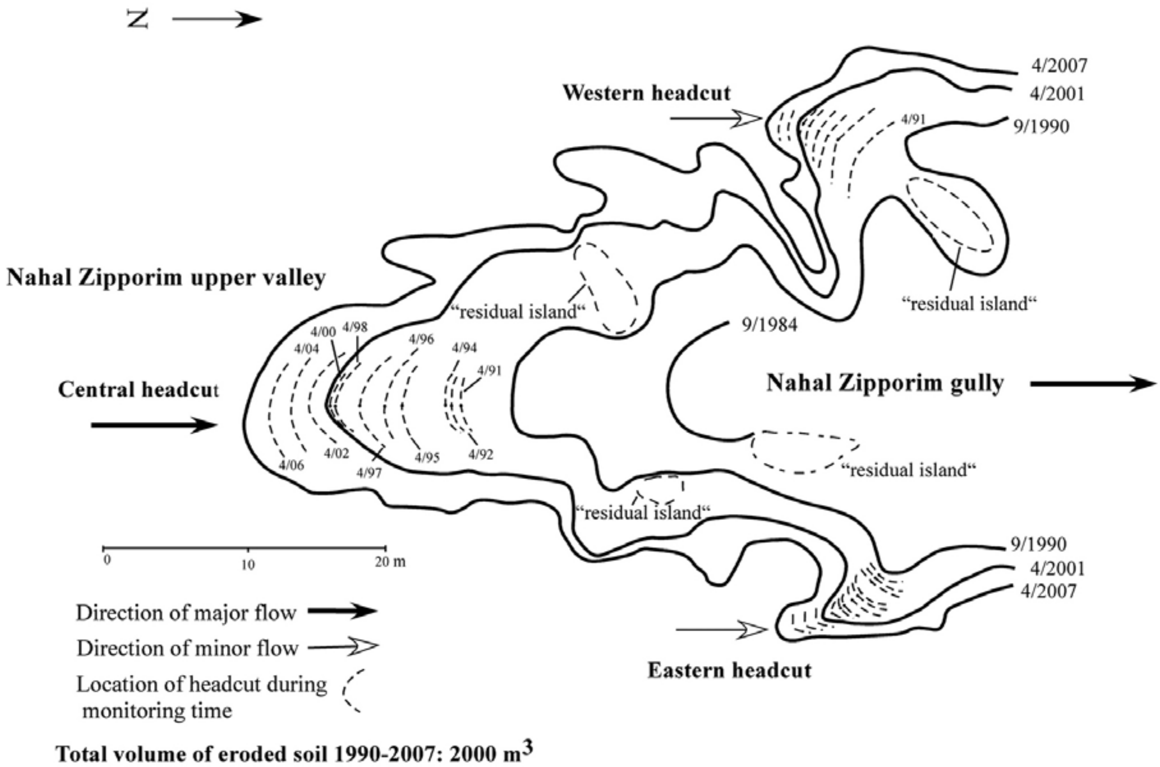

Fig. 3 Monitoring of the headcut of Nahal Zipporim, which moves upstream during flash floods. Dates of recordings are marked as month/year.

time interval (1990–2007), the total linear gully retreat in the study area ranged between 17.8 and 250 m at an average rate of 1.04–17.8 m/year for each gully head. The process was accompanied by erosion of soil, which had high agricultural and range value. The total soil losses in these sites (1990–2007) ranged between 1000 and 9000 m^3 at an average rate of 58.8–600 m^3/year for each gully head, which is equivalent to 88.2–900 t/year. During the monitoring period, approx. 0.07–0.87 ha of lands lost their agricultural and range value in each basin under study, at an average rate of 0.004–0.08 ha/year (Table 1). No recovery effects of the gully channels were found down the valley up to a distance of 15–20 km. The relatively rapid soil erosion generates an environmental change, which causes the degradation of biomass, biodiversity, grazing value and agriculture potential in the region (Avni, 2005; Avni *et al*., 2006). All these phenomena indicate that the region is under an advancing natural desertification process which is increasing in proportion to the rate of the headcut migration and gully expansion on the regional scale.

The historical and archaeological perspective

The effects of the ancient agriculture activity on the desert eco-system were studied in detail at several sites within the Negev Highlands of southern Israel, especially the Nahal Zipporim and Nahal Zena study sites (Avni, 2005; Avni *et al*., 2006) (Fig. 1). It is concluded that during the last 3000 years, and especially during the Roman-Byzantine and Early Islamic periods (2000–1000 BP), farmers built stone walls and dams to trap flood water for irrigation and to protect the fields from gully incision and soil erosion. Most of the agricultural plots were established on top of pre-anthropogenic gravelly fluvial units which were temporally deposited within the degraded valleys during the Holocene (Avni *et al*., 2006). The relation between the foundations of the agricultural installations and the natural substrate hint at aggressive soil erosion processes prevailing in the region during the early to middle Holocene. Establishment of runoff-harvesting farms since the third century AD interrupted the Holocene natural erosion and gully incision, and led to the redeposition of up to 3.5 m of fine alluvial loess sediments at a rate of up to 0.5 cm/year. The agricultural plots were sustained for hundreds of years and were constantly repaired after destructive floods (Avni *et al*., 2006).

This vast historical environmental intervention, which resulted as a by-product in the accumulation of redeposited loess sediments originating from Late Pleistocene loess sections exposed within the drainage basins, counteracted the natural Holocene trend of soil erosion. After the abandonment of the fields during the last 1000 years, natural erosion processes were re-established. It is calculated that since then, approx. 10% of the agriculture soil in the Negev Highlands region has been eroded. This study implies that fluctuations in the Holocene climate were not a significant factor in the establishment of the agricultural farms, the deposition of the fine grained sediments within them or in their abandonment.

The glacial–interglacial scale

Over 70 OSL age determinations of alluvial units deposited in the arid region of the Negev Highlands of southern Israel (Avni *et al*., 2006; Avni & Porat, unpublished report) indicate that during the late Pleistocene glacial period (OIS 4 and 2, approx. 73–20 ka), fine grained aeolian sediments were deposited within the drainage basins in the arid and semi-arid regions of the Middle East. These primary aeolian sediments were constantly washed from the hills into the valleys and redeposited with local fluvial sediments, accumulating to 6–8 m thick alluvial units. The deposition of these fluvio-loess sediments was accompanied by minor erosion cycles, documented since 27 ka (Avni *et al*., 2006). Severe erosion, such as headcuts and gullies, initiated during the Late Pleistocene OIS 2 and continued into the Holocene, resulting from the combination of reduced dust flux and higher rain intensity (Avni *et al*., 2006). This combination generated the incision of gullies and channels into the fine-grained late Pleistocene alluvial sediments, causing extended soil erosion and reducing the natural biomass. Therefore, this major pulse of erosion is attributed to natural processes, relating to a major climatic glacial–interglacial shift, which evolved long before the anthropogenic intervention became significant in the environment. As sediments older than 70 ka are rare within the drainage basins studied, it is concluded that the erosive processes active in the region during the last interglacial phase (OIS 5) were capable of eroding almost the entire alluvial section that had accumulated in the basins during the previous glacial phases.

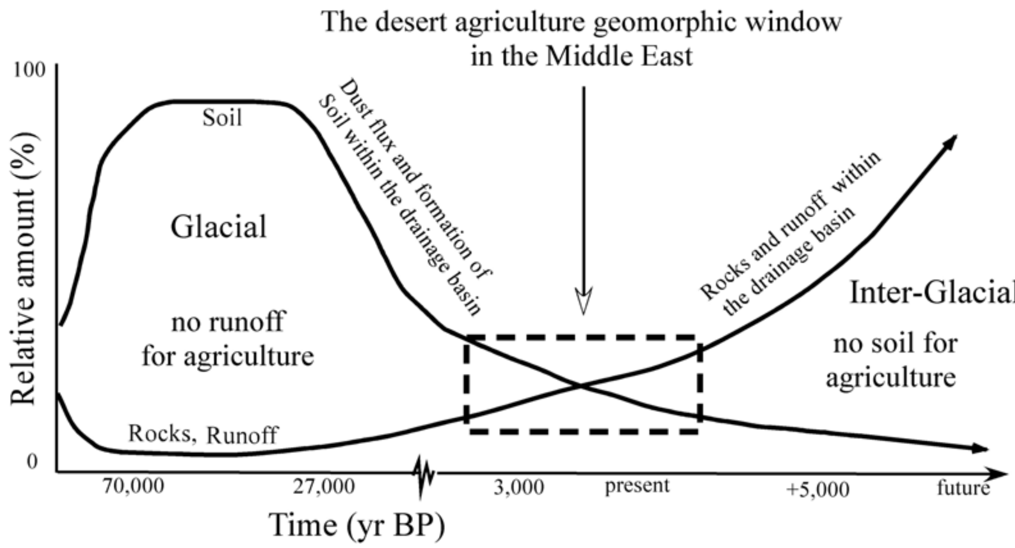

Fig. 4 A conceptual model of the natural desertification processes in the Middle East since the termination of the last glacial phase (modified after Avni, 2005).

CONCLUSIONS

The continental soil erosion in the arid and semi-arid regions of the Middle East resulted from a long-term natural dynamic change in the soil/rock ratio that evolved within the drainage basins through time. This ongoing process is related to the continuous process of adjustment of the geomorphologic system to the interglacial climate and has been active mainly since the termination of the last glacial phase in the Late Pleistocene. Under the present Holocene climate, the loess sediments, originally deposited within the drainage basins during the Late Pleistocene glacial phase (OIS 4 and 3), are being removed (Fig. 4). This ongoing natural phenomenon is causing degradation of soil and biomass and is severely reducing the agricultural and range potential of the region. Since the mid-Holocene, the co-existence of soil and runoff created unique geomorphic conditions, which enabled the establishment of agricultural farms in the arid regions of the Middle East, based on runoff-harvesting techniques (Fig. 4). The construction of the farms opposed the natural trend of soil erosion and is considered as a long-term land conservation effort applied by the ancient farmers in the arid regions of the Middle East, which was sustainable for several hundred years. It is calculated that about 10% of the agriculture soil in the Negev Highlands region was eroded during the last 1000 years. If these processes continue in the future, the Negev Highlands region will lose its agricultural potential within a few millennia.

These parameters indicate that a long-term natural desertification process is ongoing in the arid environment of the Middle East. The well-known land degradation processes caused by human activity (such as overgrazing and mismanagement of agricultural lands) is super-imposed on this natural desertification trend. Similar processes of soil erosion and ongoing natural desertification are operating in other semi-arid regions worldwide. However, the fact that ancient inhabitants of the region already implemented successful long-term land conservation techniques 2000 years ago, implies that a sustainable land management policy can be adapted to the Negev Highlands as well as to other arid and semi-arid regions in the Middle East and worldwide.

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