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Land degradation and gully development in arid environments deduced by mezzo- and micro-scale 3-D quantification – The Negev Highlands as a case study

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ABSTRACT

We study in this paper land degradation processes in arid environments that are leading to a major environmental change. These processes, which are mostly the outcome of gully development, have direct impact on agriculture potential, biomass degradation, and escalating desertification. Three representative sites within the Negev Highland, Israel, are studied by utilizing terrestrial laser scans to gain detailed spatial information, accurate estimations, and concisely document overarching trends. The resulting information allows us to thoroughly characterize and quantify the geomorphic and vegetative changes and to calibrate rates and trends that have only been roughly estimated thus far. The scans, which were taken over a four-year span (2009–2013), cover three different types of hydrological seasons and provide unique insights on development rates and subsequent ramifications. The characteristic progression of natural land degradation in the Negev Highlands and the techniques used to document and analyze it can be extended globally to regions undergoing similar transitions.

1. Introduction

Soil erosion and land degradation are common processes in semi-arid environments that lead to reduced agriculture potential, degradation of biomass, and contribute to accelerated desertification. These processes were initiated during the major climatic shift, from the last glacial era to the present inter-glacial climate, and intensified during the Holocene (Avni et al., 2006; Faershtein et al., 2016). Despite many advances in understanding the general forms of land degradation agents and their mechanisms, major challenges remain in erosion related research, control and prevention, especially in arid environments. Another aspect is the incomplete knowledge of the impact of soil erosion on sediment yield, hydrological processes, erosion rates, environmental change and landscape evolution (Boardman, 2006; Casalí et al., 2009; Leyland and Darby, 2008; Poesen et al., 2003; Poesen, 2011; Thomas, 2011; Vanmaercke et al., 2016). Of the several forms that soil erosion takes in these environments, gullying is a principle agent that causes substantial changes to the regional topography, sediment distribution, and vegetative cover (Bull, 1997; Leyland and Darby, 2008; Poesen, 2011; Torri and Poesen, 2014). Furthermore, gully development on a regional scale can lead to detrimental changes in water availability, land use, and infrastructure stability (Poesen et al., 2003; Avni, 2005).

Gully migration in southern Israel, especially in the desert land of the Negev Highlands (Fig. 1), has been documented over the last two decades using rudimentary ground measurements and observations on their long-term historical evolution and their impact on the vegetation assemblages (Avni, 2005; Stavi et al., 2010). The documentation has shown that current headcut-retreat rates range from decimeters to meters per year and display a great degree of geomorphic and ecological complexity (Avni, 2005; Stavi et al., 2010; Avni et al., 2012). However, these methods fell short of providing detailed examination and characterization of soil erosion through time, and were incapable of giving insights into the dynamics and mechanisms of the erosive processes and headcut migration which facilitate their evolution.

In order to gain better insight into the erosion processes which are acting in these environments, this paper offers quantitative high-resolution analysis of a range of characteristic sites in the 100 mm climatic zone of the Negev Highlands. The high-level characterization, which is gained through terrestrial laser scans, provides detailed documentation of the gullies and their surroundings. It thereby facilitates characterization of delicate features that have a significant impact on their evolution. The high-resolution data also allow us to thoroughly characterize and quantify the geomorphologic and vegetative changes and to calibrate rates and trends that have been roughly estimated thus

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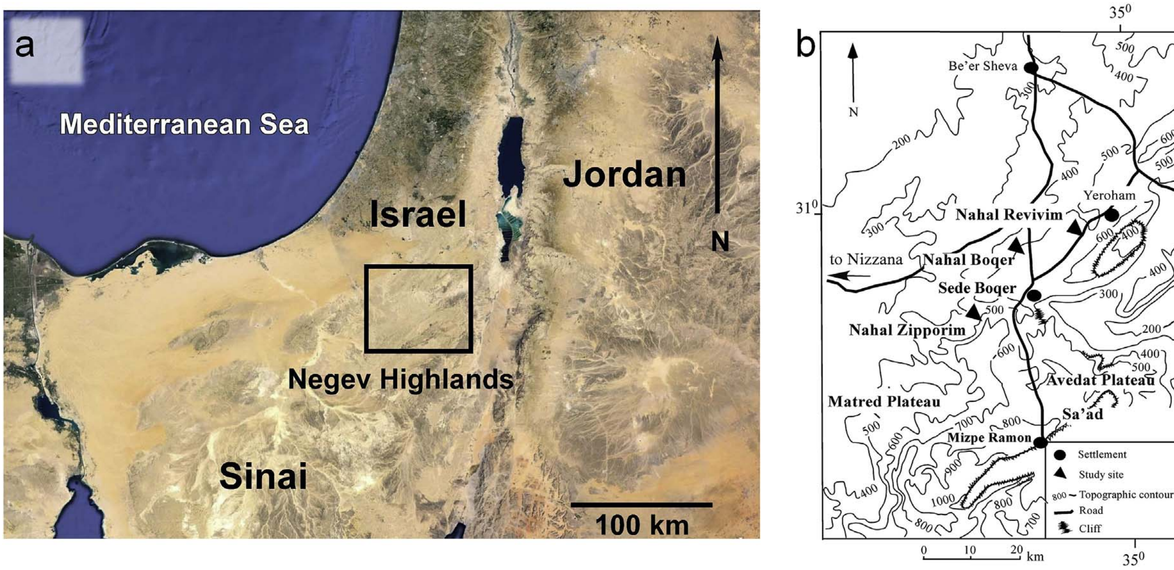

Fig. 1. Study sites location, a) The Negev Highlands, b) location of the three study sites within the Negev Highlands.

far. Our measurements, which were taken over a four-year span (2009–2013), cover a diverse range of wet hydrological seasons, from drought years to an extremely wet winter, each leading to a different style of response, allowing to analyze their impact on gully development rates and ramifications. More importantly, the wide range of observations enables to analyze the impact of the hydrological regime's strong variability (Sharon and Kutiel, 1986; Karklinsky and Morin, 2006; Thomas, 2011) on soil degradation processes.

Results of our study advance the assessment of long-term soil and sediment erosion processes in arid environments and promotes the identification and management of high-risk zones that threaten agriculture soils, biomass hot-spots, and infrastructures in arid regions. At longer time-scales, these processes contribute to understanding large-scale environmental changes that act in arid regions since the termination of the last Ice-Age and during the late Holocene. On a global scale, protocols for monitoring and managing land degradation features are indispensable for understanding its ramifications on land use, natural resources, and large-scale infrastructures such as roads, bridges, dams, pipe lines and human populations in arid environments globally.

2. Regional settings

2.1. Negev highlands

The Negev Highlands region is a rocky desert, occupying an area of approximately 3500 km^2 in southern Israel (Fig. 1). The regional topography range between 500 and 1000 m above sea level (Fig. 1b) and its rock formations are composed of marine sediments – mainly limestone, chalk, marl, dolomite, and chert layers of Upper Cretaceous to Tertiary age (Arkin and Braun, 1965; Braun, 1967; Zilberman, 1991; Avni, 1991). Several catchments drain the region toward two major water bodies – the Mediterranean Sea in the NW and the Dead Sea in the NE. The western side of the main water-divide is encompassed by two main drainage basins – Wadi El Arish and Nahal Besor, both drain large areas in the Sinai Peninsula and the Negev desert and flow towards the Mediterranean (Fig. 1). Valleys in the region are incised at depths of several tens of meters below the hills and the valley floors are between 30 and 200 m wide. Valley bottoms and hill slopes are covered with fluvial loess and gravel reaching thicknesses of 5–8 m (Fig. 2), which were deposited in the region mainly during the late Pleistocene last Ice Age and during the transition to the post glacial times, approximately 73-14 ka BP (Avni, 1991; Zilberman, 1992; Avni et al., 2006, 2012; Faershtein et al., 2016). Since the end of the Pleistocene and the start of the Holocene, the region experienced an environmental change which was manifested by a significant, naturally-driven, erosive processes, especially in the form of gully initiation and evolution (Fig. 2). In most cases, the sediments that were deposited during the glacial phase eroded under the interglacial Holocene climate. They were then re-deposited along the valleys in several cycles of cut and fill (Zilberman, 1992; Avni et al., 2006, 2012; Faershtein et al., 2016).

2.2. Present climate and flood generation

The present-day climate of the Negev Highlands is typical to most arid desert regions. Mean annual temperatures fall between 17-19 °C, the potential evaporation is approximately 2200 mm/y (Zangvil and Druyan, 1983), and mean annual precipitation is 80–130 mm with large annual variations. The rainy season occurs during the winter months from November to March. Precipitation in the region is limited as a result of drastic reductions in moisture and latent heat over the northern Sinai coastline which leads to a sharp north-to-south drop in the rainfall gradient (Vaks et al., 2006).

Frequent drought years witness more than 50% reduction in the mean precipitation and rare rainy years see a 150% increase (Yair et al., 1991; Israel Meteorological Service, 2007). In general, most of the rainfall intensity is low (less than 5 mm per hour) and is generated by the common synoptic system of the Cyprus low, which dominates the Negev Highlands winters (Sharon and Kutiel, 1986). As a result, only heavy rainstorms are capable of creating significant floods in the drainage basins. However, in small rocky basins, the thresholds to generate flashfloods are lower than in the larger ones (Yair, 1983). In addition, the rare synoptic pattern of the Red Sea low-pressure system, can lead to brief but intense rains (30–120 mm/h) that generate occasional local flashfloods typically during fall and spring times (Sharon and Kutiel, 1986). Furthermore, rain cells from this synoptic system do not exceed more than 5 km range in diameter (Karklinsky and Morin, 2006), leading to a large variability in rainfall intensity and volume between neighboring sites.

2.3. Gullies as land degradation agents

Since the end of the last Ice Age and the transition to the Holocene inter-glacial climate, rare seasonal desert storms generated high intensity rains (Sharon and Kutiel, 1986). These became runoff that cut into the unconsolidated loess sediments and created inchoate gullies (Bull, 1997; Shanan, 2000; Avni, 2005). The channeling of floodwater