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Terrace soils in the Yemen Highlands: Using physical, chemical and radiometric data to assess their suitability for agriculture and their vulnerability to degradation

D. Pietsch [a,*], L. Mabit [b]

[a] Chair of Physical Geography and Soil Science, Research area Geography, University of Tübingen, Germany
[b] Environmental Geosciences, Department of Environmental Sciences, University of Basel, Basel, Switzerland

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ABSTRACT

The Yemen Highlands are well known for their ingenious terrace systems which were constructed at the beginning of Bronze Age in the 3rd millennium BC. Although ancient, these systems are still in use, but modern erosion, deforestation, changes in climate and unsustainable qat cultivation lead to drastically increasing land degradation. A small field terrace system located in Wadi Al-Jidar/Eryan was investigated to ascertain its agricultural suitability and vulnerability to degradation of such systems while focussing on the most important base of agriculture: colluvial deposits and its associated soils. Physical and chemical analyses demonstrate that not only ancient and modern terraces both are still suitable for agricultural purposes, but that these systems are very fragile and highly erodible when abandoned. Whereas ancient and mediaeval colluvial deposits of 4 m thickness were deposited over a period of 2000 years, 2 m of modern deposits have been accumulated in 200 years only. Other noticeable differences between old and young deposits are their distinct coarse sand/fine silt contents, as well as the higher thickness of ApbBw horizons in older deposits or lower salt contents in younger soils. The present study highlights an innovative multi-radiometric (^{14}C, naturally occurring radioisotopes, ^{137}Cs) and soil data approach to evaluate the agricultural suitability of terraces in Yemen on the one hand, and emphasises several potential advantages of integrative research on land degradation on the other, particularly when investigating both ancient and modern soil erosion processes in semi-arid tropical highlands.

1. Introduction

1.1. Background

The Global Assessment of Human Induced Soil Degradation (GLASOD) survey, carried out during the 1980s by the United Nations Environment Programme (UNEP) and the International Soil Reference and Information Centre (ISRIC), established that over 45% of the Yemeni territory is characterised by severe to very severe human induced land degradation (FAO, 2005). Although the highlands of Yemen are intensively terraced, they are particularly threatened by soil erosion, and this has to be prevented and controlled as reported in the 'National Action Plan to Combat Desertification' (FAO-UNCCD-UNDP, 2000).

The investigation especially of soils and terraces in Yemen (Fig. 1) began in the framework of UNDP-FAO projects of the 1970s, when the agricultural suitability of field terraces and the quality of soils for crop production became increasingly important (Sharma and Awad, 1976, 1977); at this time major modifications of the agrarian sector were taking place (Kopp, 1981). The main cause of socio-economic changes in Northern Yemen in the 1970s was the migration of Yemeni people to the oil countries, which led to the abandonment of villages and fields (Steffen, 1981; Vogel, 1988).

For this purpose a country wide soil survey was accomplished in the 1980s, which resulted in 1:500,000 soil map of Yemen (King et al., 1983) followed by a 1:1,000,000 scale published in 1988 by the Tübinger Atlas des Vorderen Orient (TAVO) project (Straub, 1988). Following these basic inventories, investigations on modern terracing, soil erosion, water availability and vegetation in the highlands of Yemen were carried out, e.g. in the framework of German Technical Cooperation (GTZ) projects (Al-Hubaishi and Müller-Hohenstein, 1984; Müller-Hohenstein et al., 1987; Rappold, 2000, 2005; Straub, 1986; Vogel, 1987, 1988). Ancient agriculture in Yemen has become a topic of geoarchaeological investigations in the last three decades (Edens and Wilkinson, 1998; Kühn et al., 2010; Pietsch and Morris, 2010; Varisco, 2000; Wilkinson, 1997, 2003, 2005). In this context it was discovered that, despite intensive terracing in ancient Yemen, extreme soil erosion already occurred during the transition from the Mid to Late Holocene, mainly during peak seasonal precipitation. As the climate became drier during this period, precipitation events became episodic and the discharge behaviour of wadi floods was modified (Wilkinson, 2005). Soil and climate change research in Yemen conducted in recent years has highlighted these drastic climatic changes

* Corresponding author. Tel.: +49 7071 2977533.
E-mail address: dana.pietsch@uni-tuebingen.de (D. Pietsch).

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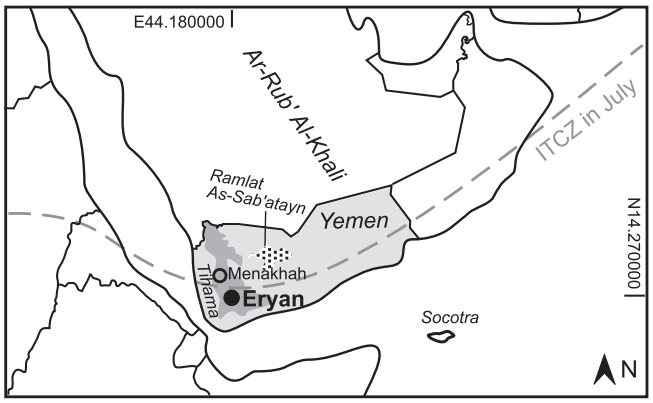

Fig. 1. Location of Wadi Al-Jidar/Eryan and of the main comparative study site Menakhah. Ibb and Rehab (cf. Table 1) are situated near to Eryan.

in Southern Arabia (e.g. Fleitmann et al., 2007; Lézine et al., 2007; Parker et al., 2006; Pietsch and Kühn, 2009; Pietsch et al., 2010; Sirocko et al., 1993; Wilkinson, 2005). Few studies of afforestation, a very important strategy for soil protection and for combating soil erosion, have been reported in Yemen. For example, deforestation of *Juniperus* sp. woodland, assumed to have been distributed throughout the highlands of Southern Arabia in ancient times, has been mentioned in the literature but until now this issue has not been investigated in detail (Gardner and Fisher, 1994; Hepper and Wood, 1978). Only one study of land evaluation between Sana'a and Dhamar exists (Dent and Murtland, 1990). Erosion modelling in Yemen has so far only been included in an eco-hydrological erosion model of Wadi Surdud using GIS techniques (Naoman, 2005).

What makes the terraces in Yemen so ingenious? Since ancient times terrace walls have been constructed which accumulate colluvial deposits for agricultural use (Varisco, 2000; Wilkinson, 2005). First, a low stone wall is erected and material is deposited behind the wall; later fine materials (suspended particles) are flushed during rainfall events and are accumulated slowly (Kopp, 1981; Vogel, 1987). Terraces are also found at middle and lower altitude wadi courses with low inclination and expanded wadi beds, albeit with fluvial characteristics, but they similarly have been cultivated until modern times with fruit trees, sorghum and vegetables (Kopp, 1981; Pietsch, 2001; Straub, 1986; Vogel, 1988). Soil erosion in terraced areas – in the present case in an area with steep slopes of Tertiary basalt and tuff and its highly erodible weathering products – was a direct consequence of unsustainable land use, beginning around the 1970s, and this not only in Yemen (cf. Anderson and Thampapillai, 1990). Land degradation due to erosion leads to a decline in productivity over time and to a reduction in the actual and potential use of the land (Blaikie and Brookfield, 1987; Dalelo, 2001; Nyssen et al., 2008). In addition, as the inclination of slopes increases, water erosion is even more marked (Cerdá and García-Fayos, 1997), and in the Yemen Highlands, slopes with high inclinations of more than 30° are used for agriculture. Today, because of long-term changes in climate and socio-economic circumstances and land use conversion from coffee to qat, half of the terraces in the highlands of Yemen have been partially or fully destroyed.

1.2. Aims of the present study

The main objectives of the present study are to compare field terraces of different age, thickness and layering by considering the composition of the colluvial material and secondary soil formation. The aim is to assess (a) the agricultural suitability of accumulated materials and (b) the vulnerability of terraces to degradation due to soil erosion. Whereas modern erosion rates of the last 50 years can be determined by the ^{137}Cs-method, ancient erosion can be estimated by ^{14}C dating (Brakenridge, 1985). We assume that concurrent dating and stratigraphic studies of deposits help to estimate rates of sediment deposition.

With regard to modern erosion after 1950, one of the first steps was to establish a naturally occurring radioisotope (NOR) and ^{137}Cs base-line dataset of an undisturbed terraced site in Wadi Al-Jidar/Eryan (Al-Qafer district, Ibb governorate). The next step will be the assessment of the magnitude of erosion and sedimentation processes affecting the local terrace system from the 1950s to the present, and to prove our hypothesis whether or not significant allochthonous eolian deposit could be accumulated on lower terraces and mixed with local basaltic parent material of soil formation. All together, this integrative approach will be used for future assessments of modern and ancient soil erosion rates at the catchment scale in the Yemen Highlands.

1.3. Comparative study sites and available data

A study on terraces and soil erosion in the region of Menakhah (cf. Fig. 1) was published by Vogel (1987, 1988). Together with data from the region around Eryan/Ibb/Rehab (King et al., 1983; Pietsch, 2001; Sharma and Awad, 1977), Vogel's (1988) study can be seen as the most important comparative database when discussing our results from Eryan, because mountainous relief, Tertiary alkaline rocks (Kruck et al., 1996), mean annual precipitation (MAP) of <1000 mm (Bruggemann, 1997), crops such as sorghum, maize as well as orchard, and the character of sedimentary and pedogenic processes are similar to the present study area. Besides terrace systems and the socio-economic consequences of being abandoned, these studies yield information on rainfall erosivity and infiltration, water erodibility of soils, soil properties and the availability of plant nutrients such as plant available phosphorous (P_{av}) and plant available potassium (K_{av}) (Table 1).

From the studies of Sharma and Awad (1977), King et al. (1983), Vogel (1988) and Pietsch (2001) profiles comparable to our study area have been chosen: (i) soil parent materials that are mainly weathering products from alkaline Trap basalt and tuff, and some loess, (ii) mean annual precipitation of approximately 450 to 800 mm (Bruggemann, 1997), and (iii) profiles are located at elevations between 1100 and 2200 m, all being part of terrace systems in different slope positions (Fig. 2).

High precipitation in the northern and central highlands coupled with high rainfall erosivity (cf. Table 1), a decreased infiltration rate in abandoned terraces of 3 cm h^{-1} (in contrast to extreme infiltration rates of 11 cm h^{-1}, Vogel, 1988: 75), a high gravimetric soil moisture content of 12.5% after rainfall (Vogel, 1988: 58) and the mechanical breakdown of many terrace walls leads to the loss of fertile soil by sheet and gully erosion. Single heavy rainfall events with 50 to 60 mm precipitation per day are indicators for potential gully erosion in the area of Menakhah; between 1978 and 1985 these occurred 2 to 4 times per year (Fassbender, 1982). Sheet erosion also appears as a result of more gentle rainfall events, and in abandoned terraces with silty and loamy substrates bearing no vegetation, the silt fraction of the top soil is eroded immediately (Vogel, 1988).

1.4. Advantages of soil erosion research by using ^{137}Cs

Since there is no precise and recent data on the erosion magnitude for Yemeni terraces in the area of Tertiary basalt, the determination of the current soil degradation rate could be evaluated through the use of fallout radionuclides (FRN). Traditional erosion and sedimentation methods are limited in their capacity to provide quantitative short and mid-term trends in soil erosion. However FRN, especially ^{137}Cs, are effective isotopic tracers to assess soil erosion magnitudes and the extent of erosion within agricultural landscapes from plot to basin scale integrating inter-annual, mid-term climatic variability and