Catena 171 (2018) 251–264

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Quantifying the effectiveness of mountain terraces on soil erosion protection with sediment traps and dry-stone wall laser scans

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ARTICLE INFO

Keywords:
Soil water erosion
Agricultural terrace
Mediterranean vineyard
Monitoring experiment
Sediment traps
Terrestrial laser scanning

ABSTRACT

Mountain depopulation in the Mediterranean region over the past decades has led to a decline in the use and maintenance of agricultural terraces and consequently the collapsing of dry-stone walls, which can increase soil erosion rates and downstream sedimentation. A field experiment has been set up on a degrading terraced hillslope in the Troodos Mountains of Cyprus, to quantify the effectiveness of terrace maintenance on protecting cultivated land against soil erosion. The monitored site is cultivated with grapes. The terrace riser (22 m long) that forms the linear outlet of the hillslope has 11.4 m of standing dry-stone wall and 10.6 m of collapsed wall. It has been instrumented with seven 1 m wide sediment traps, three on standing sections of the wall and four on collapsed sections. When dry, sediment was collected from the traps after rainfall events, from December 2015 to November 2017. Uncertainties in the drainage areas of the 31.5-m long slope were quantified both for the terrace wall and for the individual traps through hydrologic delineations based on a detailed topographic survey. The sediment data were complemented by laser scanner surveys that were conducted in November 2015, May 2016 and April 2017, on a dry-stone terrace wall upslope from the outlet section. Wall degradation was assessed from the consecutive 3D model reconstructions. Rainfall was 469 mm in the first year and 515 mm in the second year and the average erosivity was 1148 MJ mm ha^{-1} h^{-1} y^{-1}. The average soil erosion rate was 2.4 Mg ha^{-1} y^{-1}, when linear drainage areas are considered (693 m^2), 3.2 Mg ha^{-1} y^{-1} when the borders are delineated with the topographic data (520 m^2). Nearly half of the soil erosion (43%) occurred during two very intense rainfall events (maximum 30-min intensity exceeding 35 mm h^{-1}), out of the 34 monitored events. Erosion from standing terrace sections was 3.8 less than the erosion from the collapsed sections. For the scanned terrace wall, soil erosion from the standing sections was 2.2 lower than from the degraded sections. The laser scanner surveys identified some preferential erosion paths, but failed to recognize single stone collapses, whereas possible wall displacement was masked by scanning artifacts. The sediment traps were found to be an effective method for understanding and quantifying soil erosion in terraced mountain environments, while further research is needed to develop a more rigorous acquisition procedure for laser scanner surveys to derive useful information on wall degradation.

1. Introduction

Dry stone walls have been built around the Mediterranean basin for millennia (Tarolli et al., 2014). In Cyprus, dry stone terraces date back to the Bronze Age (Fall et al., 2012). In general, terraces were created to allow agriculture in mountain environments, and served to reduce the degrading effect of soil erosion by controlling the surface runoff velocity and facilitating water infiltration in the soil. Terraces act as sediment traps storing the washed-off soil material within the hillslope. The sediment that accumulates behind the dry-stone walls creates suitable land for farming. Although their main purpose is food production, terraces have been also recognized as sustainable land management practices for water retention and control of soil erosion in sloping environments (Li et al., 2014). Dry-stone terraces provide an intensive cultivation form, which requires little mechanical aid but high input in terms of labor (Rolé, 2007).

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https://doi.org/10.1016/j.catena.2018.07.017
Received 20 February 2018; Received in revised form 30 June 2018; Accepted 16 July 2018

In the steep mountainous areas of Cyprus, erosion by water is a key soil threat (Zoumides et al., 2017). Around the small rural communities in the mountains, large areas have been converted into agricultural terraces, mainly for vineyard cultivations. Similarly, to many other rural areas in the Mediterranean (e.g. see García-Ruiz and Lana-Renault, 2011), the population of the communities in the Troodos Mountains, the main mountain range of the island, has decreased substantially over the past 30 years. As a result, many of the mountain terraces are no longer cultivated and terrace walls are poorly maintained, if at all, causing a progressive degradation of the landscape. In some areas completely abandoned long ago, nature is taking over, thus reducing soil erosion. In such cases, soil erosion is more gradual than on recently abandoned or poorly maintained land, as it has also been observed in other terraced (e.g., Brandolini et al., 2017; Modica et al., 2017) and non-terraced (e.g., Nasta et al., 2017) areas in the Mediterranean Region.

A limited number of studies have tried to quantify soil erosion in terraced environments, either through field research or modelling or both (Dorren and Rey, 2004; Koulouri and Giourga, 2007; Lesschen et al., 2008; Arnáez et al., 2011; Bevan and Conolly, 2011; Nunes et al., 2016; Djuma et al., 2017). The observations and results of these studies are highly contrasting, and a wide range of soil erosion rates have been reported (0.015–87 Mg ha^{-1} y^{-1}). The effectiveness of well-maintained terraced hillslopes, as opposed to poorly-maintained terraced hillslopes or natural hillslopes, also varies widely in the literature, subject to different climatalogical conditions (Chow et al., 1999; Dorren and Rey, 2004).

Conversely, due to their socio-economic importance, extensive literature can be found about soil erosion rates in vineyards. Prosdocimi et al. (2016) published a comprehensive review study, in which they create a database of erosion rates in the Mediterranean Region. In doing so, the authors quantitatively summarize the role of different erosion factors, as also investigated by many recent studies (e.g. Biddoccu et al., 2017; Cerdà et al., 2017; Napoli et al., 2017; Rodrigo Comino et al., 2016; Lieskovsky and Kenderessy, 2014). Although vineyards on terraces are mentioned, no specific analysis of these environments is included, neither as topographical characteristic nor as soil conservation technique. A recent review study by Rodrigo Comino (2018) focused on soil erosion rates in vineyards around the world. The author derived ranges of soil erosion rates based on the location (country) of study areas and the methodological approach. Also, he suggested to include social and economic aspects in soil erosion studies to help farmers apply effective management strategies. The author did not specifically consider the presence of agricultural terraces or other conservation practices in the reviewed studies, he only mentioned that poorly designed structures can canalize water and increase sediment loss.

In the last decade, ground-based laser and imaging techniques have been increasingly developed and applied in various geoscience domains, due to the growth of computing capabilities, the development of high performance digital sensors and the booming of visual software innovations (Eltner et al., 2016; Westoby et al., 2012). Their application in soil erosion assessments include various studies that compared simple and low-cost Structure from Motion (SfM) techniques with more expensive, high accuracy ground-based LiDAR acquisitions (e.g., Gomez-Gutierrez et al., 2014; Smith and Vericat, 2015). In this regard, Prosdocimi et al. (2015) found SfM methods to be comparable with Terrestrial Laser Scanner (TLS) acquisitions in terms of accuracy, recognition of erosion areas, and calculation of eroded volumes, while analyzing river bank erosion features. Nouwakpo et al. (2016) compared the two techniques on both bare and vegetated soils (up to 77% cover). They found that the two techniques are both reliable and comparable to each other on bare soil, while on vegetated areas the combination of the two techniques leads to the best recognition of changes in the micro-topography. Eltner and Baumgart (2015) looked specifically at the accuracy constraints of TLS methods for multi-temporal surface changes detection. DeLong et al. (2018) applied repeated TLS surveys to monitor post-wildfire soil erosion in the lower 2.7 ha of a catchment (75 ha in total) located in Arizona, USA. The method allowed to recognize and differentiate effects of different erosional processes (overland flow, rill, gully, deposition) by detecting changes in the topography down to 5 mm. Previous studies on post-wildfire erosion (e.g. Staley et al., 2014; Orem and Pelletier, 2015) applied multi-temporal TLS surveys and detected sub-centimeter topographic changes, too. Other studies focused on the reconstruction of 3D models with SfM to determine the evolution of rills and gullies (Di Stefano et al., 2017; Frankl et al., 2015). These authors showed the effectiveness of these methods, which on average led to errors in the calculation of eroded volumes lower than 15% compared to traditional measurement techniques, namely profilometer and measuring tape. Soil erosion processes have been also studied by TLS at the laboratory scale (e.g. Balaguer-Puig et al., 2017). Preti et al. (2013) performed TLS scans to obtain a front-viewed 3D digital model of a dry-stone retaining wall. The resulting model had a resolution of 0.01 m, allowing recognition of single wall stones, and was optimal for stress-strain stability simulations. In addition, Preti et al. (2013) and Tarolli et al. (2015) used TLS surveys to derive high resolution Digital Terrain Models (DTMs) to perform a hydro-geomorphological analysis of terraced vineyards. They used the DTMs to recognize preferential accumulation flow paths caused by terraces and applied the Relative Path Impact Index (RPII) proposed by Tarolli et al. (2013). However, no comprehensive study can be found in the literature that combines sediment loss measurements by traps or troughs, with multi-temporal TLS surveys to quantify erosion from hillslopes with degrading dry-stone walls.

The overarching goal of this study is to quantify the effectiveness of maintaining and restoring terraces retained by dry-stone walls for reducing soil erosion by water. Specifically, a monitoring experiment was set up: i) to compare erosion rates from non-degraded (standing) and degraded (fully or partly collapsed) dry-stone wall sections and to quantify the amount of soil eroded in a typical terraced vineyard, ii) to analyze relations between erosion from terraces, rainfall, erosivity and runoff; iii) to complement traditional soil erosion measurements (soil traps) with dry stone wall degradation observations derived from terrestrial laser scans.

2. Case study area and monitoring site

Mountain agriculture in the Troodos Mountains of Cyprus consists mainly of small, poorly maintained, terraced plots cultivated for family use. According to the declared 2016 agricultural plots, as registered in the Cyprus Agricultural Payments Organization (CAPO) database, grape, fruit trees and nuts are the main crops at elevations above 800 m a.s.l. These crops occupy 690 ha, 676 ha and 16 ha, respectively, out of a total declared agricultural area of 1817 ha. The average plot size is 0.16 ha for grapes, 0.11 ha for fruit trees, and 0.08 ha for nut trees. The average slope of the Troodos region above 800 m a.s.l. is 42%.

The monitoring site is located in the upstream part of the 112-km^2 Peristerona Watershed, on the northern slope of the Troodos Mountains. A map showing the location of the case study area and monitoring site is presented in Fig. 1. The upstream area ranges from 900 to 1540 m a.s.l. and has a mean slope above 40%. Intrusive rocks (gabbro, diabase and basal group) of the Troodos ophiolitic sequence dominate its geology. The main land cover comprises of sclerophylous vegetation and mountain agriculture on dry-stone terraces. The average annual precipitation is around 750 mm (1980–2010), with daily extremes that can reach up to 170 mm (Camera et al., 2014a). Temperature ranges from an average daily minimum temperature of 3 °C in January and February to an average daily maximum temperature of 31 °C in July and August. In general, the Troodos Mountains are characterized by a warm temperate climate, with most rainfall occurring during the winter months, which is typical for the Mediterranean region (Zittis et al., 2017).

The monitoring site is a hillslope cultivated with grapes, located in