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Erosion processes in calanchi in the Upper Orcia Valley, Southern Tuscany, Italy based on multitemporal high-resolution terrestrial LiDAR and UAV surveys

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ABSTRACT

A 125,000 m^2 calanchi badland in the Province of Siena (Tuscany) was monitored with an unmanned aerial vehicle (UAV) and terrestrial laser scanning over the period of one year. TLS (terrestrial laser scanning) was carried out on two sample slopes, whereas the image acquisition of the UAV covered the entire catchment. In combination with ground control points, the UAV images were used to create orthophotos and 3D point clouds using the Structure from Motion (SfM) software Photoscan. The TLS surface models indicate seasonal differences in erosion and deposition. The surface change measured with SfM showed nearly 6.700 m^3 of net material loss, resulting from 8.700 m^3 erosion and 2.000 m^3 deposition. These values reveal a mean annual surface lowering of 5.3 cm for the catchment. Additionally, several geomorphological processes, such as rill erosion, slope wash and translational slides could be detected in the one-year monitoring period. A comparison of TLS and SfM results showed differences in the calculated volumes of mobilised material. These discrepancies resulted from shadowing effects and low point densities of the TLS point clouds.

1. Introduction

Badland development is an often-addressed issue in geomorphological research because it leads to a variety of problems such as loss of agricultural land. Faulkner (2008) gives an overview on past badland research and explains badland dynamics by introducing a closed system model focussing on energy utilisation and shifts in power and connectivity. Frequently observed geomorphic processes in badlands are rilling (Wirtz et al., 2012), gullying (Peter et al., 2014), piping (Gutiérrez et al., 1997; Faulkner, 2013) and gravitational mass movements (Desir and Marín, 2013). Especially gully development has the potential to degrade large areas of land surfaces including cultivated ones (Poesen et al., 2003).

Badland landforms can be found in several Italian regions and are locally called "calanchi" (singular: "calanco") and "biancane" (singular: "bianco"). Alexander (1982) gives an overview on differences between calanchi and biancane badlands in Italy. Many studies on Italian badlands were carried out in Tuscany (e.g. Phillips, 1998; Della Seta et al., 2007; Ciccacci et al., 2008; Vergari et al., 2011; Aucelli et al., 2014). Castaldi and Chiocchini (2012) investigated the geomorphology of calanchi in Tuscany, focussing on the effects of land use change on erosion. Della Seta et al. (2007, 2009) and Ciccacci et al. (2008, 2009) evaluated erosion rates and morphodynamics in Tuscan badlands. Della Seta et al. (2009) focus on the space-time variability of erosion processes at the hillslope scale, whereas Bollati et al. (2012) used dendrochronological analysis to date denudation processes. Outside the Tuscan region, Moretti and Rodolfi (2000) studied geomorphological features and the evolution of calanchi in the Abruzzo region. Even in the southernmost regions of Basilicata (Clarke and Rendell, 2006; Farifteh and Soeters, 2006) and Sicily (Pulice et al., 2012), the development, the origin and the process–form relationships of calanchi were analysed.

Several studies focussed on soils and substrate in calanchi areas. Piccarreta et al. (2006), Pulice et al. (2012) and Vergari et al. (2013a) analysed the physico-chemical properties of parent material. Grain size analysis, soil mineralogical analysis, and geochemical analysis of the substrate were carried out by Battaglia et al. (2003) and Summa and Luigia (2013) in relation to badland development. GIS-based morphometric analysis of calanchi has been published (e.g. Buccolini and Coco, 2010, 2013; Caraballo-Arias et al., 2014). Vergari et al. (2011) assessed landslide susceptibility in the Upper Orcia Valley, Tuscany with GIS and statistical methods. Long-term erosion rates were

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evaluated by Aucelli et al. (2012, 2014) with photogrammetrical analysis of aerial images dating back to 1954.

Up to now, direct measurements of erosion rates in calanchi areas were mainly carried out with metal stakes, i.e. erosion pins (e.g. Clarke and Rendell, 2006; Della Seta et al., 2007, 2009; Ciccacci et al., 2008, 2009; Cappadonia et al., 2011; Vergari et al., 2013a). A major disadvantage of this classical field method is its low spatial resolution, as it is not possible to install enough pins to identify processes such as rotational and translational slides. Furthermore, slopes are affected directly by the person measuring erosion depth. Therefore, remote sensing has opened opportunities for analysing badlands as it has the ability to produce high resolution topographic data. Satellite imagery (Liberti et al., 2009; Nadal-Romero et al., 2012), images from manned gyrocopters (Smith and Vericat, 2015), UAV imagery (d'Oleire-Oltmanns et al., 2012; Ouédraogo et al., 2014; Peter et al., 2014), terrestrial imagery (Kaiser et al., 2014) and laser scanning (Abellán et al., 2009; Schürch et al., 2011; Haas et al., 2012; Vericat et al., 2013) are widely used for badland research.

This study aims to quantify and analyse erosion processes in a Central Italian calanchi area during one year. Data from TLS (terrestrial laser scanning) with high temporal and spatial resolutions are used in order to identify processes involved in calanchi development. Test slope sites were monitored with repeated TLS measurements in order to analyse seasonal differences. Additionally, data from two survey campaigns with an unmanned aerial vehicle were used to create digital elevation models and orthophotos of the entire catchment. DEMs from TLS and SfM (Structure from Motion) serve to evaluate annual surface lowering rates. The produced orthophotos and on-site campaigns served as a basis for vegetational and geomorphological mapping of the research site. Because several existing studies focused on the accuracy of TLS and SfM methods (e.g., James and Robson, 2012; Fonstad et al., 2013; Kaiser et al., 2014; Ouédraogo et al., 2014), we did not aim to analyse the accuracies of both methods in detail.

2. Study area

2.1. Geographic setting

The research area is a calanchi dominated catchment, located in the Tuscan Pre-Apennines about 6 km NNW of Radicofani Town (Province Siena, Italy) (Fig. 1). It spans an altitude from 500 to 650 m a.s.l. and covers an area of ~125,000 m^2. It is part of the Upper Orcia river basin, which is the easternmost part of the Ombrone river basin. The climate is temperate-warm with an average annual precipitation of around 700 mm, with extremes ranging from 500 to 1100 mm (Aucelli et al., 2014) and a mean temperature of 14 °C. The thermal regime shows a range of 18 °C with its maximum in July and August (Vergari et al., 2013b). As it is typical for the Mediterranean region, the rainfalls are concentrated in winter and autumn with a maximum during November. In contrast, summers are hot and dry with least precipitation in July (Aucelli et al., 2014). Vergari et al. (2013b) state that the semi-arid conditions during the summer months followed by heavy rainfalls in autumn, even some consecutive rainy days, are probably an ideal combination for fluvial erosion on the clayey calanchi slopes. The spring months, in contrast, are the time where shallow translational landslides occur. After the long wet period, the soils are sufficiently saturated and the superficial slides are easily triggered by a secondary rainfall peak (Della Seta et al., 2009; Vergari et al., 2013a).

2.2. Geological and geomorphological setting

The Radicofani graben is an NW–SE striking graben structure dating back to the Miocene as a consequence of an eastward verge of the Tuscan and Ligurian thrust sheets (Ciccacci et al., 2008). This graben structure was subsequently filled with marine and terrestrial deposits during the Pliocene and Pleistocene. Caused by a regional arching, these Plio-Pleistocene marine deposits were raised far above the present-day sea level (Ciccacci et al., 2008; Vergari et al., 2013b; Aucelli et al., 2014). These marine deposits locally crop out at 900 m a.s.l. at the Mt. Amiata-Radicofani neck and the Mt. Cetona in the southernmost part of the Radicofani graben, where the uplift has been particularly fast (Vergari et al., 2013b). The outcropping rocks are predominantly clays and sandy clays from the Lower Pliocene, which are very prone to erosion processes (Aucelli et al., 2014).

The hilly landscape is dominated by two types of badland landforms: biancane and calanchi. The occurrence of rounded-edged biancane is normally attributed with gentle dipping slopes, where the biancane are located either on top of the hills or at the slope foots (Della Seta et al., 2007). Biancane landforms are characterised by steeper south-facing slopes that are free of vegetation (Ciccacci et al., 2008). The south-facing slopes are predominantly formed by slope wash and piping processes.

Calanchi landforms appear on strongly inclined slopes and affect most of the valley slopes at the channel heads (Ciccacci et al., 2008). The term calanchi derives from the latin verb chalare, which means "to deepen" or to "excavate". Alexander (1980) describes calanchi as an "extremely dissected, rapidly developing landscape with a very fine-textured drainage network". Rodolfi and Frascati (1979) identified two main types for the calanchi in Tuscany, which was expanded with one more type by Ciccacci et al. (2008):

- Type A, which can be referred to the typical "knife-edged" type. It develops on clayey substrata with a high silt and sand content. Concentrated surface runoff leads to sharp and dissected landforms with a dense drainage pattern and deep V-shaped channel profiles.
- Type B has a less dense drainage pattern and evolves typically from recurring superficial slides on unweathered substratum. The valleys are, in contrast to Type A, trough-floored and separated by small convex ridges.
- Type C shows a much higher frequency of mass movements. A great amount of small landslides is about to destroy the calanchi ridges and fill up the bottom of the valleys.

2.3. Slope locations monitored with TLS

Surface changes were monitored using TLS at two slopes (Fig. 1). One slope is located in the northern part of the catchment, where rotational slides had occurred. On-site visits and the DEM reveal at least two rotational slide events. The older one is recently damming the upper part (~3500 m^2) of the catchment, causing a large flat vegetated area forming the valley bottom upstream. The upper part of the younger rotational slide slipped about 20 m downslope from the tear-off edge.

The second slope (with an area of 3030 m^2) is located in the south-western part of the calanchi area. It has predominantly south, south-westerly aspects and an average slope inclination of 41°. Vegetational areas account for 825 m^2 and bare substrate accounts for the remaining 2205 m^2 at the slope.

3. Methods and materials

3.1. Terrestrial laser scanning (TLS)

Terrestrial laser scanning (TLS) or LiDAR (Light Detection And Ranging), has become a well-established tool in geosciences. Data acquisition was carried out using two different Riegl Laser Measurement Systems: LMS-Z420i and VZ 4000. Both systems are based on the time-of-flight principle and operate with wavelengths in the near infrared (NIR). The rotating mirror allows a point sampling of several thousand points per second. An on-top mounted Nikon D70 DSLR on the LMS-Z420i and an internal calibrated digital camera in the VZ 4000 are used to acquire high resolution images of the scanned objects. These images are helpful for a later filtering of vegetation, as they are used to colourize