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Abstract

Agricultural landscapes cover a significant part of the Earth. In floodplains, we can find large areas dedicated to intensive agriculture. However, also on hills and mountains, agricultural activity can be relevant from the socio-economic point of view. Nowadays, such areas are increasingly under threat because of global environmental changes. Widespread growing rainfall aggressiveness due to climate change, in addition to land abandonment, lack of structural maintenance, and in some cases unsuitable agronomic practices are exposing steep-slope agricultural landscapes to increased hazard of landslides. A suitable hazard assessment and zonation of these phenomena would help better management of such agricultural landscapes. The purpose of this article is to provide an overview of this relevant problem focusing on (i) the contribution of remote sensing technologies (e.g., LiDAR and UAV photogrammetry) in mapping the investigated processes, and (ii) discussing advances and limitations of susceptibility modelling.

Keywords Landslide - Remote sensing - Modelling - Landscape - Agriculture

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Landslides in Steep-Slope Agricultural Landscapes

Paolo Tarolli, Anton Pijl, and Sara Cucchiaro

Abstract

Agricultural landscapes cover a significant part of the Earth. In floodplains, we can find large areas dedicated to intensive agriculture. However, also on hills and mountains, agricultural activity can be relevant from the socio-economic point of view. Nowadays, such areas are increasingly under threat because of global environmental changes. Widespread growing rainfall aggressiveness due to climate change, in addition to land abandonment, lack of structural maintenance, and in some cases unsuitable agronomic practices are exposing steep-slope agricultural landscapes to increased hazard of landslides. A suitable hazard assessment and zonation of these phenomena would help better management of such agricultural landscapes. The purpose of this article is to provide an overview of this relevant problem focusing on (i) the contribution of remote sensing technologies (e.g., LiDAR and UAV photogrammetry) in mapping the investigated processes, and (ii) discussing advances and limitations of susceptibility modelling.

Keywords

Landslide • Remote sensing • Modelling • Landscape • Agriculture

Background

Agricultural land use is responsible for an unprecedented transformation of natural environments worldwide, with vast and long-term impacts on geomorphology and soil properties (Baartman et al. 2012). Cultivated areas typically involve reduced soil cover and cohesion, which particularly in steep-slope environments greatly affect soil erosion and slope instability (Koulouri and Giourga 2007; Prosdocimi et al. 2016; Tarolli and Straffelini 2020). Several researchers around the world have studied the increased landslide susceptibility of cultivated hillslopes, and several factors related to agricultural practices (i.e. not considering climate or slope steepness) have been discussed. Agricultural transformation affects soil stability due to the removal of permanent deep-rooted vegetative cover (Perotto-Baldiviezo et al. 2004), while the natural soil structure is affected due to land levelling (DeGraff and Canuti 1988; Ramos et al. 2007). In addition, an unsuitable or degraded terracing or drainage system can further aggravate landslide hazard (Tarolli et al. 2014). This is often related to the lack of maintenance as a result of land abandonment and loss of labour, as widely reported for Mediterranean (Arnáez et al. 2017; Cevasco et al. 2014; Tarolli et al. 2014) and Asian steep-slope agricultural areas (Gerrard and Gardner 2002; Raj Khanal and Watanabe 2006). Other factors include the cultivation and subsequent reactivation of dormant landslides (Sugawara 2013), and the construction of agricultural roads for machinery (Tarolli et al. 2015). The latter is able to divert runoff and create concentrated patterns of water flow, which are often related to the initiation of landslides (as illustrated in Fig. 1).

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The high landslide hazard in agricultural areas can have considerable impact on production and human safety. Nonetheless, reliable inventories are missing for many marginalised steep rural areas around the world. Modern developments in remote sensing, computer technologies and models may help contributing to this. In this work, we discuss the opportunities and challenges of remote sensing techniques, digital terrain analysis and landslide modelling, based on literature and few original examples.

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Fig. 1 Landslides that occurred after an intense rainfall event in a typical steep-slope vineyard terraced landscape. Landslide crowns are highlighted with a white dashed line (Photographs by P. Tarolli)

Remote Sensing

Techniques

Landslide inventory maps are generally limited in terms of spatial coverage and time period (Guzzetti et al. 2012), which can partly be attributed to the intensive mapping methods used in the past (Galli et al. 2008). However, there is a strong potential to address this gap by the use of modern remote sensing techniques, which allow more accurate topographic analysis by use of faster and cheaper surveys (Tarolli 2014). The most recent platform that proved highly successful is the use of an Unmanned Aerial Vehicle (UAV, sometimes referred to as UAS or RPAS) and the parallel development of Structure from Motion (SfM) photogrammetry technique (Giordan et al. 2018), which allows high-accuracy surveying by low-cost applications of a simple drone mounted with a non-metric camera (Fig. 2). This platform rapidly gained popularity for mapping topographic features, as it is flexible to deploy in varying conditions (including difficult-to-access sites) and is able to capture complex geomorphologic features (Eltner et al. 2016; Cucchiaro et al. 2018). The typical coverage of light-weight UAVs is in the order of tens of hectares and is optimal for agricultural conditions (Colomina and Molina 2014; Pijl et al. 2020). Indeed, specific examples of UAV-based analysis of agricultural slope failure can be found, e.g. for monitoring mass-movements (Lucieer et al. 2014; Turner et al. 2015), or for the detection and modelling of terrace failures (Pijl et al. 2019).

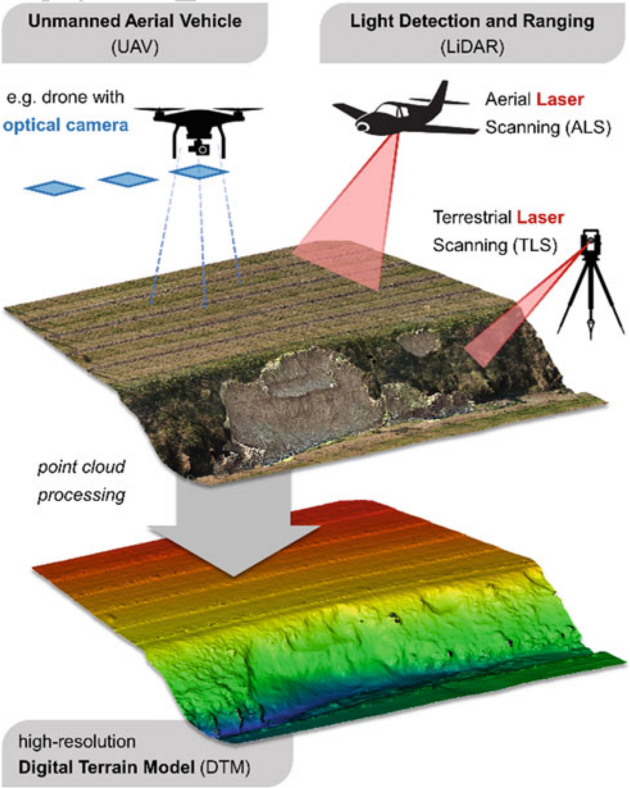

Fig. 2 Schematic illustration of the creation of a high-resolution Digital Terrain Model (DTM) by remote sensing techniques of Unmanned Aerial Vehicles (UAVs) or Light Detection and Ranging (LiDAR) instruments (Sample dataset from original data by the authors)

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Another modern remote sensing technique that is commonly used for high-resolution topographic mapping is Light Detection and Ranging (LiDAR) from a terrestrial or aerial platform (Fig. 2). It is probably one of the most popular technique in landslide research, by providing highly-detailed topographic information for the detection, monitoring or modelling of slope failure (Jaboyedoff et al. 2012; Scaioni et al. 2014). Although LiDAR involves considerably higher deployment costs than UAV-based surveys (Guzzetti et al. 2012), it offers a major advantage over the latter due to its ability to retrieve multi-layered return signals and resulting ground detection in densely vegetated areas (Tarolli 2014). As such, it is probably the most established platform for geomorphologic research, and countless examples can be found of LiDAR-based research of agricultural landslides, e.g. in Italian terraced landscapes (Preti et al. 2018a; Tarolli et al. 2014, 2015; Giordan et al. 2017; Brandolini et al. 2018).

Digital Terrain Analysis

The improving spatial accuracy of topographic data (e.g. from UAV or LiDAR source) also allows higher accuracy in the detection of landslides and their geomorphology. Basic 2-D digital terrain analysis can be used to support visual detection, while facilitating more advanced purposes such as volume estimation, multi-temporal monitoring and susceptibility modelling (as discussed in the following chapter). Several authors have tested the use of terrain derivatives such as slope, surface roughness or curvature for the automatic delineation of geomorphologic features using a statistical threshold (McKean and Roering 2004; Booth et al. 2009; Tarolli et al. 2012). In this work, we illustrate this concept using an original topographic data sample, consisting of a road-induced landslide (Fig. 3). The shaded 0.05-m DTM clearly shows how the landslide crown is captured, appearing as a dark edge at the road side. This crown presents a disruption with respect to the surrounding geomorphology, as can be identified using the surface roughness index (Fig. 3), here calculated according to Cavalli et al. (2008) using a 31-cell kernel. Similarly, high values of maximum landform curvature indicate convex terrain elements (according to Evans 1979 using a 31-cell kernel); and the statistic threshold approach by Sofia et al. (2014) has been be used to automatically extract the landslide crown (Fig. 3). This approach could rapidly be applied over large extents, hence becoming a powerful tool for automatic geomorphologic feature extraction.

Modelling

For estimating the susceptibility, or spatial probability of slope failures occurrence, numerous models are available (Guzzetti et al. 2005), but the number of publications on landslide hazard assessment in steep agricultural slopes is still rather modest. In this anthropic context, further variables must be considered than the classic ones used to better describe the landslide triggering processes. Here, slope failure hazard is not only dependent on meteorological events and geotechnical land attributes, but also agricultural practices and human activities can strongly affect the occurrence of instability phenomena (Shrestha et al. 2004). For example, Perotto-Baldiviezo et al. (2004) developed and tested a spatial model for predicting the spatial distribution of landslide hazard in steep areas of Honduras considering four model variables as slope, aspect, stream proximity and land cover type. Their results highlighted how. As the slope increased, the percentage of land affected by landslides, increased sharply on cropland when the soils were saturated. This indicated that agricultural activity and the associated removal of deep-rooted permanent vegetation increased the landslide hazard on steep sites. Jaiswal et al. (2010) also proposed a probabilistic landslide model to quantify hazard of first-time slope failure on natural slopes and tea plantations, underlining how agricultural and constructional activities make an area more susceptible to landslides. At the local scale, numerical simulations must consider the presence of widespread agricultural practices such as terraces that heavily influence the hydrological processes (Gallart et al. 1994; Preti et al. 2018a) and can trigger superficial mass-movements when they collapse. Camera et al. (2014) analyzed the processes that can lead to failure. They used a numerical modelling of groundwater movement and related stability analysis, to provide pore water pressure distributions, which are generated by different rainfall amounts, as parameters for a stress-strain analysis that can directly determine the influence of various rainfall parameters on dry-stone wall stability. Penna et al. (2014) evaluated the predictive power of the quasi-dynamic shallow landslide model QD-SLaM (Tarolli et al. 2008) to simulate shallow landslide locations in a small-scale steep-slope watershed. The study area represented a typical anthropogenic Mediterranean landscape, with terraces (partly abandoned), roads and a village. The applied landslide model did not incorporate the description of road-related or terrace-related failures, thus highlighting its limits in the correct interpretation of hydrological processes in an anthropogenic context. The model predictive power was shown to be

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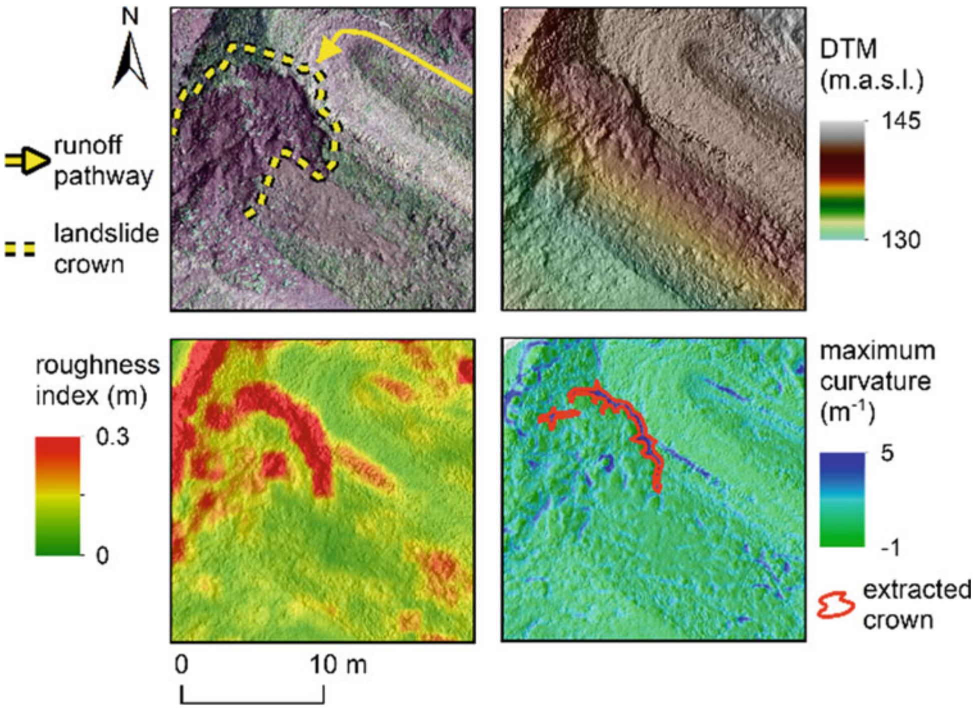

Fig. 3 Example of a landslide induced by a runoff pathway on a curving agricultural road (top-left, yellow lines). Additionally, illustrated are the shaded high-resolution DTM derived by UAV-SfM workflow (top-right), and two terrain derivatives: the roughness index (bottom-left) and the maximum landform curvature (bottom-right). The latter shows the automatically extracted landslide crown using a threshold approach (red outline). (Sample topographic dataset with 0.05-m spatial resolution by the authors)

DTM-resolution dependent. The use of a coarser resolution had a smoothing effect on terrain attributes, and therefore on predictive model performance. The authors concluded that to realize the full potential of high-resolution topography thus including anthropogenic geomorphic features, more extensive work is needed to specifically identify the extent of the artificial structures and their impact on shallow landsliding processes. Tarolli et al. (2015) used LiDAR elevation data for a detailed hydro-geomorphological analysis of terraced vineyards. The geomorphic Relative Path Impact Index (RPII) was tested in two vineyards to identify terrace-induced and road-induced erosion. Using such an index, the authors then simulated different scenarios of soil conservation measures, establishing the optimal solution to reduce erosion. The results highlighted the effectiveness of high-resolution topography in the analysis of erosion at the local scale of terraced vineyards when surface water flow is the main factor triggering the instabilities. An example of the predictive power of RPII in the recognition of potential slope failure in a steep-slope terraced site is shown in Fig. 4, where we considered the case study of Fig. 1.

Preti et al. (2018b) proposed a more specific model able to describe hydrological processes in terraced landscapes. In detail, they analyzed the destabilizing pressures acting on the retaining dry-stone walls in the most critical portion of each terrace. The results showed good capability of the model to

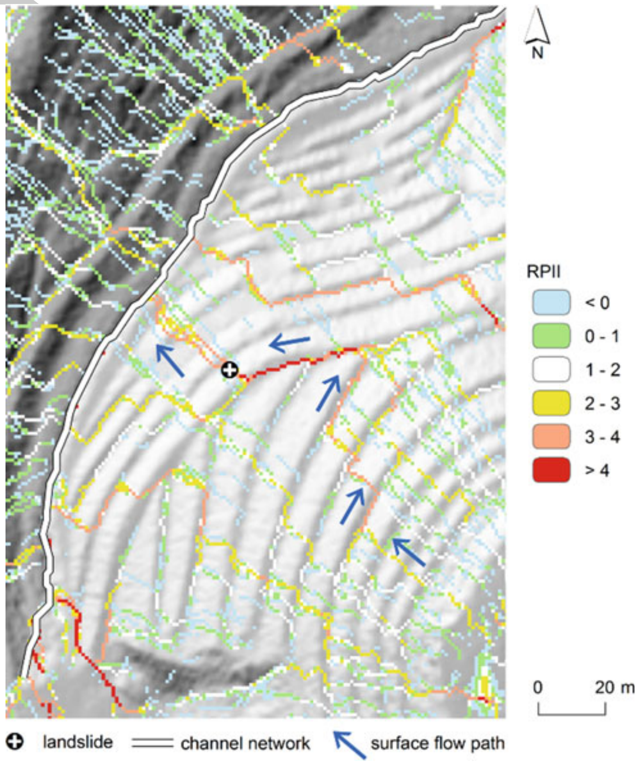

Fig. 4 Relative Path Impact Index (RPII) calculated for the case study shown in Fig. 1 using a 1-m LiDAR-derived DTM. Surface flow modifications induced by an agricultural road and consequent landslide (warm colours) match well with the location of the observed landslide (plus symbol), thus confirming the predictive power of the index for the detection of slope failure in this context

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predict the distribution and intensity of stress on the dry-stone wall over time and space. This stress was related to the combined earth pressure and hydrostatic pressure (water accumulation), without the occurrence of soil saturation. A better understanding of the main hydrological processes that govern surface and subsurface water flow pathways and that are responsible for terrace failure is essential for appropriate water resource management and rural landscape maintenance in terraced areas (Preti et al. 2018a). Such insights could support landowners and land planners in managing these complex and fragile environments.

Final Remarks

Climate change (e.g., the increase of rainfall intensity) and changing societal trends (e.g., land abandonment) are aggravating land degradation in agricultural landscapes, resulting in increased mass movements that should not be neglected. Not only does this affect agricultural production, it also poses a risk to local communities of people. Several approaches for the spatial analysis of such processes are available, however high-resolution topography derived by modern remote sensing techniques (e.g., SfM photogrammetry using UAV images, or airborne or terrestrial LiDAR data) is highly recommended for the detection of the characteristic local-scale geomorphic features usually visible with sub-meter DTM grid cell size. In addition, it is also recommended to improve the understanding of the main hydrological processes that govern surface and subsurface water flow pathways. Existing modelling approaches seem to be not optimal for a satisfactory understanding of such processes. Indeed, to meet the full potential of high-resolution topography, they should be designed to include the anthropogenic geomorphic features and model their impact on the physical processes or vice versa. More recently, few authors developed some advances along this line. This will absolutely be a future challenge for scientific studies in this field. Novel insights from research could support land owners and land planners in managing these complex and fragile landscapes, in order to preserve cultural heritage, ecosystem services, and food safety while maintaining the economic and environmental sustainability.

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