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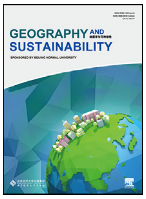


Perspective

Agriculture in Hilly and Mountainous Landscapes: Threats, Monitoring and Sustainable Management

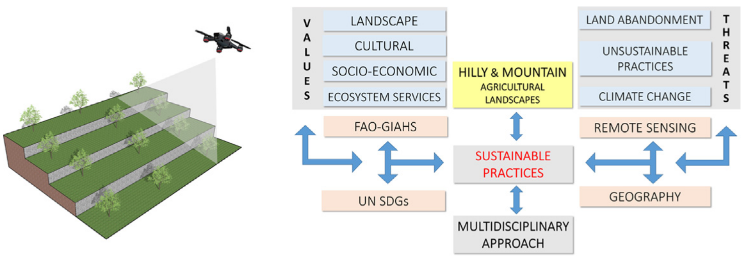
Paolo Tarolli*, Eugenio Straffelini

Department of Land, Environment, Agriculture and Forestry, University of Padova, Agripolis, Viale dell'Università 16, Legnaro (PD) 35020, Italy

HIGHLIGHTS

- Agricultural landscapes cultivated in hilly and mountainous regions are susceptible to soil loss.
- Land abandonment, heavy-mechanization, climate change are accelerating land degradation.
- Geography may become a valuable asset for the mitigation of hydrogeological risk.
- Remote Sensing and digital terrain analysis could help in planning sustainable interventions.

GRAPHICAL ABSTRACT



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ABSTRACT

Agricultural landscapes cultivated in hilly and mountainous areas, often with terracing practice, could represent for some regions historical heritages and cultural ecosystem services. For this reason, they deserve to be protected. The complex morphology that characterises them, however, makes these areas intrinsically susceptible to hydrogeological instability, such as soil loss due to surface erosion or more severe mass movements. We can identify three major critical factors for such landscapes. The first is related to the socio-economic evolution of contemporary civilization, that increased the land abandonment of several rural regions, leading therefore to a lack of maintenance. A second element is the unsustainable agricultural practices, such as excessive heavy-mechanization that cause soil compaction thus accelerating degradation. Finally, the climate change forcing, with the increasing of the extreme rainfall. In this complex framework, it is necessary to find innovative solutions for the mitigation of hydrogeological risk and to respond in a well-prepared way to the possible future critical scenarios. Therefore, the use of sustainable agricultural practices, which allow the production of quality agricultural products in perfect harmony with the surrounding environment, becomes crucial. Suitable solutions must respond to the criterion of multidisciplinary, where the various stakeholders collaborate by offering their specific knowledge in a shared intention of problem-solving. The discipline of geography may become a valuable asset in this framework. In particular, thanks to the recent technological advances in the topographic survey (e.g. innovative remote sensing techniques such as drones and airborne laser scanning), it is possible to exploit digital terrain analysis to synthesize key information for decision-makers, in order to plan sustainable interventions. Moreover, thanks to the high-resolution and accuracy offered by digital topography and the advanced morphometric algorithms, it is possible to tackle the problem of hydrogeological risk from a unique and privileged perspective: that of prevention.

1. Agricultural landscapes

Since ancient times, humans have developed techniques to satisfy their basic needs, primarily the production of food for the sustenance of society. For this reason, it has developed agricultural systems adapted to the geographical context in which they are located, creating a harmony between the necessity to suit the needs and sustainability in the use of

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* Corresponding author.
E-mail address: paolo.tarolli@unipd.it (P. Tarolli).
URL: http://orcid.org/0000-0003-0043-5226 (P. Tarolli)

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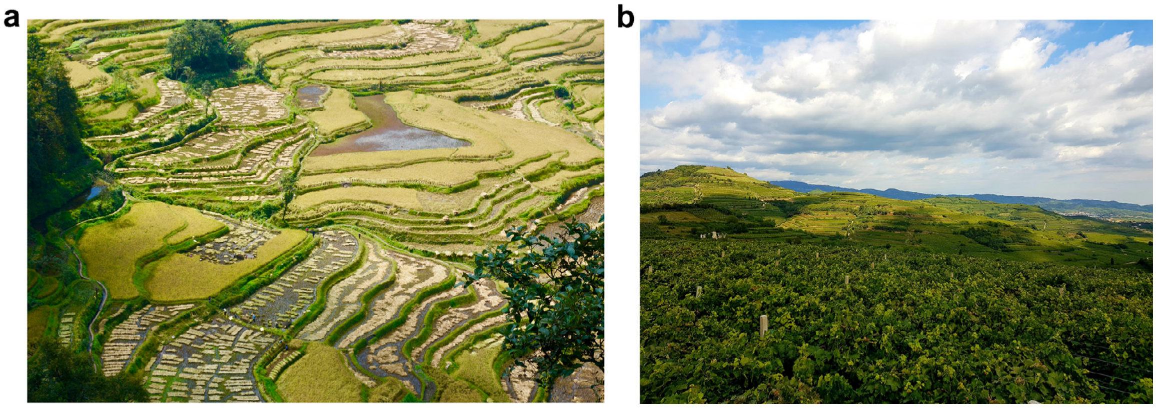

Fig. 1. (a) Example of agricultural landscape cultivated with rice (Honghe Hani Rice Terraces FAO-GIAHS site, Cultural Landscape Heritage, Yuanyang County, Yunnan, PR China; photo by P. Tarolli) and (b) grape according to traditional terracing practice (Soave FAO-GIAHS site, Cultural Landscape Heritage, Northern Italy; photo by P. Tarolli).

resources. This efficient management, combined with the respect for the surrounding territory, has historically led entire communities to use traditional farming systems for their livelihoods. This highlights the value of resilience as a key element for adapting to constantly evolving socioeconomic and environmental conditions (Jiao et al., 2012). Through centuries and in an increasingly anthropocentric cultural context, humans have been able to shape the surrounding land for its sustenance (Tarolli et al., 2019). This is leading to a profound modification of the landscape through the spread of agricultural practice, which assumes a multifunctional role (Varotto et al., 2019). In fact, if in its primordial form agriculture was considered only as a food production system, now it is also recognized as a distinctive feature of a territory, capable to offer an identity. From the strong interaction between "natural" and "anthropic" actors on Earth surface, the concept of landscape was born, defined as "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (European Union, 2000). Landscape, in its complexity of forms and elements in balance with each other, becomes the essence of territory and place where people, customs, traditions and historicity coexist. This is the case of cultivated lands in mountainous regions, where the presence of terraces is often observed as an optimal agronomic practice for a different type of cultivation (e.g. rice, grapes, olives, among others, Fig. 1).

Agricultural terraces offer an important benefit to the territory thanks to the ecosystem services they offer (Wei et al., 2016). In fact, they are historically used for levelling the soil and to reduce the gradient of the slope, thus facilitating cultivation operations. They favour the infiltration of water, making it more available to crops and controlling the velocity and quantity of surface runoff, also facing the soil erosion phenomena (Tarolli et al., 2014). In addition, they can also serve as habitat-providers and offer ecological corridors for biodiversity (Diaz-Varela et al., 2014).

The terraced system on steep slope is however very susceptible to hydrogeological instability if not carefully managed (Tarolli et al., 2014). The abandonment of cultivated land (and thus the lack of maintenance), the increase of rainfall intensity due to climate change, and the introduction of heavy or non-optimal mechanisation worsened their susceptibility to erosion (Pijl et al., 2019a; Tarolli et al., 2019b). In general, the recognized value of traditional rural landscapes now under these threats, has led the Food and Agriculture Organization (FAO) of the United Nations (UN) to launch the Globally Important Agricultural Heritage Systems (GIAHS) programme, with the aim of protecting, preserving and managing traditional agricultural knowledge and the landscapes in which they develop (FAO, 2018a). Formally, GIAHS are defined as "Remarkable land use systems and landscapes which are rich in globally significant biological diversity evolving from the co-adaptation of a community with its environment and its needs and aspirations for sustainable development" (FAO, 2010). Since 2002, the program aims to identify the sites characterized by the presence of agroforestry and pastoral systems managed through traditional agricultural practices sustainably adapted to the environment. At the present 59 GIAHS sites worldwide are distributed in 5 macro-regions and 21 countries. There are several sites worldwide where hill and mountain farming has high historical and cultural value. In particular, where the slopes are very steep, it is often supported by the presence of terraces. We can mention two useful examples of such landscapes (one for Asia and one for Europe) that differ in culture, climate, history, materials, and cultivation systems: "Honghe Hani Rice Terraces" (Yunnan Province, P. R. China) (Fig. 1a) and "Soave Traditional Vineyards" (Veneto Region, Northern Italy) (Fig. 1b), awarded in 2010 and 2018 respectively (FAO, 2019). In the former, people of various minority ethnic groups, with Hani as the main representative, created an integrated terraced farming system involving cattle, ducks and fish farming to support rice production (FAO, 2020a). The second site aims to protect the traditional hillside viticulture of the Soave wine, which has been practised for centuries through a sustainable management system that promotes the uniqueness of the landscape (FAO, 2020b). Here, the so-called "heroic viticulture" survives. Vines are grown on terraced steep slopes designed with the traditional techniques, where it is possible to obtain market-competitive wines, appreciated by consumers and with a unique and distinctive taste (Capece et al., 2012).

2. Land abandonment, unsustainable practices, climate change

Agriculture has undergone a huge expansion by changing land use, guaranteeing world population growth. On the other hand, however, this has also led to a strong acceleration in the rate of erosion (Montgomery, 2007; Tarolli and Sofia, 2016), so much that the soil is globally lost at a greater magnitude than that produced by mechanisms of regeneration (Amundson et al., 2015). To understand the significance of the phenomena, it is necessary to mention that from 2001 to 2012, at a global level, the potential soil loss increased by 2.5%. This was due to a change in land use of about 4 million square kilometres, mainly resulting from forest decline and expansion of semi-vegetable areas (savannah, bush, grassland, transitional forest) and cultivated areas (Borrelli et al., 2017). In detail, soil erosion caused by water (surface runoff and drop erosivity) is one of the major threats to soil, causing a negative impact on ecosystem services, agricultural production, drinking water and carbon stocks (Panagos et al., 2015). This is also the case of the terraced areas, which allows the cultivation of grapes (in the case of the Mediterranean region) in hills and mountains (Prosdocimi et al., 2016). This tradition management practice is however very fragile. Particularly, these areas are often characterized by a complex morphology, even induced over the centuries by human beings to support the needs of cultivation. If from

Fig. 2. A landslide occurred after a high-intensity rainfall event in a terraced vineyard landscape in North of Italy (photo by P. Tarolli).

the landscape , historical, economic and cultural point of view they represent a real heritage, on the other hand, they are therefore intrinsically fragile and susceptible to hydrogeological risk and soil erosion (Fig. 2).

We can identify three major critical factors for such landscapes. The first is linked to the abandonment of the land. A first reason is still to be found in the evolution of the cultivation technique: the introduction of machinery is leading to the concentration of viticulture in more morphologically accessible area (e.g. gentle slope surfaces or floodplains). In addition, a profound socio-economic change that has caused the depopulation of agricultural areas in favour of cities has led to a gradual abandonment of mountain landscapes (Torquati et al., 2015), contributing to an increase in soil erosion and land degradation (Brunoni et al., 2018) due to the lack of maintenance of drainage systems (Pijl et al. 2019b), and the decline of the traditional sustainable agricultural knowledge. The second element is mechanization, increasingly frequent also in high steep hilly and mountain agriculture, to respond to modern cultivation practices. The introduction of heavy or non-optimal machinery causes considerable pressure on the terrain, leading to soil compaction (Batey, 2009; Bogunovic et al., 2017), and a significant soil degradation phenomenon found in a wide range of soils and climates around the world (Hamza and Anderson, 2005; Schreck et al., 2012). This problem affects both lowland (Jabro et al., 2014) and mountain crops, as well as terraced farms (Stanchi et al., 2012) and hillslope vineyard (Bidoccu et al., 2016, 2017; Capello et al., 2019). It induces serious disturbances to the pore system, changing the spatial distribution, size, diameter and number of cavities (Horn et al., 1995). The result is a profound alteration of the soil from a chemical, physical and biological point of view. Particularly, it is noticed a reduction in the permeability of air and water, with a consequent increase in surface runoff and erosion (Batey, 2009). To understand the influence of this factor it is possible to observe the situation of Italian vineyards cultivated in terraced high-steep slope landscapes. It was observed, using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), that the potential erosion is 37% higher in mechanised fields than in non-mechanised fields, mainly due to the reduction of soil permeability (Pijl et al., 2019a). A further critical factor, to be added to previous, is climate change. The first noteworthy and potentially critical aspect is the temporal evolution of average precipitation. Globally, it has been estimated that during the 21st Century the frequency and intensity of precipitation will tend to increase with high probability (IPCC, 2019).

As example, the Northern Italy, an economically important region for wine production, would expect an increase of rainfall event by the end of this century (Gao et al., 2006; Zollo et al., 2016), a trend already observed for the past century (Sofia et al., 2017). Rainfall is a factor capable of inducing soil erosion both through the erosive effect of raindrops and runoff (Zuazo et al., 2005). In conclusion, considering the iteration between a complex morphology, the use of unsustainable agricultural practices or the abandonment of terraces and the occurrence of climate change, soil erosion becomes a serious problem to be treated with the utmost sensitivity.

3. A multidisciplinary approach to sustainability

In September 2015, more than 150 international leaders met at the United Nations to discuss an environmental-sustainable global development with a vision of improving human well-being. As a result, the Agenda 2030 for Sustainable Development, a document composed of 17 Sustainable Development Goals (SDGs) and 169 sub-targets, was approved. Aims are to end poverty, combat inequality, build peaceful societies and fight climate change promoting sustainable social-economic progress and by achieving the objectives before 2030 (United Nations, 2015). One ambitious SDG is the number 2: “End hunger, achieve food security and improved nutrition and promote sustainable agriculture”, which aims to eliminate hunger around the world. Indeed, malnutrition affects nearly 800 million people, especially women and children, often due to environmental degradation, drought and loss of biodiversity (United Nations, 2020a). For this reason, sustainable agriculture plays a key role in achieving objectives set by the SDG2, and an indicator has been specifically dedicated to it to assess progress towards the final objective of the 2030 Agenda (Goal 2 - Target 2.4 - Indicator 2.4.1: “Proportion of agricultural area under productive and sustainable agriculture”) (United Nations, 2020b). According to this indicator, the sustainability of an agricultural practice must be assessed in the economic, social and environmental context. It must combine the themes of productivity, profitability, resilience, land/water management, decent work and well-being, in order to capture its multidimensional nature (FAO, 2020c). And it is precisely on this complex nature that governments, non-governmental organisations (NGO), scientists and stakeholders should focus to ensure that sustainable agriculture spreads throughout the world. In addition, to do so, it must raise awareness that only a multidisciplinary view of the problems affecting the environment will enable the formulation of appropriate solutions. Particularly, in an articulated system such as the high-steep slope terraced hillsides, the sustainability of agricultural practice must manifest in all its components, especially if it is aimed at mitigating erosion (Lesschen et al., 2008). In order to achieve this condition, the cultivation must be correctly and efficiently maintained in all its parts (Moreno-de-las-Heras et al., 2019), through systematic planning of interventions. Water regulation is fundamental, as one of the major causes of instability (Preti et al., 2018). It must take place through the design of a drainage network for surface runoff, with particular attention to the viability that requires tailored interventions. Also important is the correct management of the interaction between water and for example dry-stone wall (where these represent the main agricultural practice), providing drainage to avoid collapse due to excessive water load behind the wall. When a terrace is hydraulically and structurally efficient, sustainability is also measured in agricultural management practices. Fundamental, in the case of vineyards, is the use of appropriate herbaceous species in the inter-row as grass cover (Morvan et al., 2014). Strategic is the use of native species of the place of cultivation, as they promote the development of biodiversity and the reduction of soil erosion. In order to limit excessive compaction, it is also advisable to reduce the use of heavy mechanization to the minimum and to plan ripping interventions to increase the water infiltration capacity of the soil. A promotion of new light solution of mechanizations, even using animals (e.g. in the case of Honge Hani Rice Terraces), through appropriate subsidies from local governments, is highly recommended. A terrace is, therefore, a micro-world where environmental, ecological and climatic factors coexist with humans in perfect synergy. Sustainable agriculture must be able to find the right balance between factors, providing a quality product while respecting the surrounding environment. To guarantee this, a multidisciplinary ap-

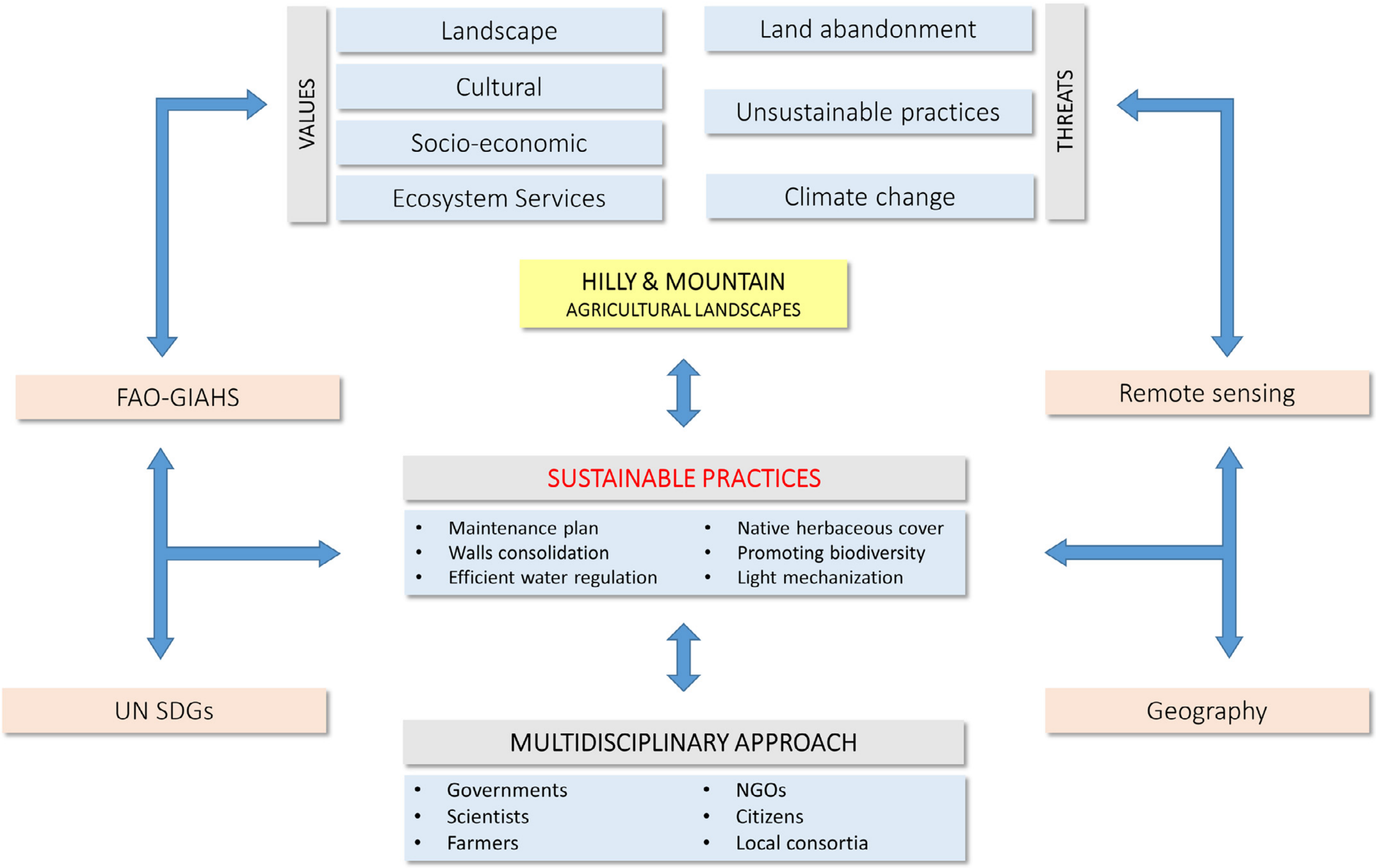

Fig. 3. Framework for monitoring and sustainable management of hilly and mountainous agricultural landscapes.

proach is an indispensable value, as well as graphically summarized in Fig. 3.

Consequently, the involvement of several actors with different experiences and backgrounds, but joined in the creation of a sustainable food production system plays a key role, also in achieving the objectives of the SDGs in agreement with the FAO guidelines (FAO, 2018b). Of crucial importance in a context of sustainability is also the role of the citizen, as part of a community that lives the agricultural landscape and recognizes its identity in it. An example of how the citizens receive an indirect benefit from the care of the land and the sustainability of agricultural practices is eco-tourism. In fact, there are many cases all over the world, such as within the FAO-GIAHS sites, where an agricultural landscape rises into a “cultural tourism landscape” (Sun et al., 2011). A virtuous example of multidisciplinary-based project, involving partners from the academic world (e.g. University), farmers (e.g. wine producers), local stakeholders (wine consortium, land reclamation authorities), private research labs and consultants, and private mechanization companies, have been activated in 2019 in the FAO-GIAHS site “Soave Traditional Vineyards”, North of Italy. It is called SOiLUTION SYSTEM (www.soilutionsystem.com) and supported by the EU Rural Development Programme (Programma di Sviluppo Rurale per il Veneto 2014-2020). The aim is developing an integrated system of technologies and management approaches, environmentally and economically sustainable, to reduce erosion and improve the soil in steep-slope vineyards where hydrogeological risk is high. Innovative tools for the topographical survey will be used (e.g. drones), along with new instruments to monitor precipitation erosivity. Newly-designed, low-impact tractors will be developed to cultivate steep-slope vineyards, and innovative technologies to manage and consolidate terraced vineyards. Overall sustainability of the approach will be evaluated and improved.

4. The role of remote sensing & high-resolution topography

Problems affecting the environment require an in-depth comprehension of all processes involved (natural and anthropogenic). In this challenge, the geography discipline can help by offering a range of innovative tools for landscape knowledge. The rapid evolution of technology that characterized the recent decades has allowed the development of powerful instruments for obtaining and managing spatial data, useful to convert big data into simple essential information for decision-makers (Hardin and Hardin, 2013). Remote sensing techniques for the observation and understanding of Earth’s surface processes (Lillesand et al., 2015) and Geographical Information System (GIS) for data management (Parker, 1988) are key examples. Another interesting aspect of this technological revolution is linked to the accessibility; nowadays high-tech becomes accessible to a large number of people in a relatively short time. As an example, is possible to cite the airborne and terrestrial laser scanners (lidar), and Unmanned Aerial Vehicles (UAVs), or drones. A first important issue is to understand the spatial scale with which such methods work. Through the use of the airborne laser scanner (lidar), it is possible to detect large areas of territory, offering a detailed 3D reconstruction at a regional scale (Hansen et al., 2014). Then it is possible to analyse the features of the terrain and to understand its morphology. For example, in the case of steep hilly and mountain agriculture, it has been demonstrated that using this type of data it is possible to identify and extract terraces (Cao et al., 2020; Sofia et al., 2014). The use of drones, on the other hand, makes it possible to work at a lower spatial scale, for example at farm level, but with greater resolution, usually 20-50 cm/pixel (Turner et al., 2012). Therefore, the high-resolution models allow the recognition of microtopography, relevant for the understanding of processes that take place on the surface (Nouwakpo et al., 2016). Focusing on the environmental science field, knowing how to exploit

Fig. 4. Survey of a hillside vineyard using a drone and GNSS to measure the position of the Ground Control Points, indispensable for georeferencing data (photo by S. Cucchiaro).

these technologies could provide a breakthrough in the search of innovative problem-solving solutions. A virtuous example is the case of the photogrammetric technique called "Structure-from-Motion" (SfM) (Eltner et al., 2016), combined with the use of drones, to analyse the hydrogeological instability phenomena (Giordan et al., 2018).

SfM is a photogrammetric technique that provides the creation of a three-dimensional representation of an object through the mathematical interpretation of a series of images taken according to precise technical rules (Recker et al., 2014). The top-view perspective offered by the drone, combined with the use of a GNSS (Global Navigation Satellite System) to improve the quality of the result and for its georeferencing (Fig. 4), allows the representation of 3D digital terrain model of the Earth's surface. The output of photogrammetric processing consists of a point cloud, a set of a large number of known-coordinates points plotted in space based on a reference system. These are also the results of other methods and tools of topographic surveying, such as lidar (light detection and ranging), which is more expensive (however more useful in some conditions since it is possible to penetrate vegetation) if compared to SfM from UAVs. Working in geomorphology it is important to identify which points represent the bare ground soil, in order to obtain a basis for understanding its features. For this reason, in photogrammetry as well as for lidar, a point cloud filtering phase is necessary (Zeybek and Şanlıoğlu, 2019). Through different filtering algorithms, it is possible to classify points as "ground" and "non-ground" (vegetation, buildings, artefacts, etc.). The points of the terrain are then interpolated to create a digital terrain model (DTM). The pixel size represents the resolution of the model: a smaller dimension leads to a higher resolution. This geographical data, opportunely managed in a GIS (Geographic Information System) environment, represents a powerful tool of knowledge of a territory, as it allows the elaboration of several geomorphological elaborations for the understanding of the physical processes taking place on Earth. In a complex context such as high-slope terraced areas, hydrological processes are mainly driven by topography, where the greatest weight-factor is the slope (Tarolli et al., 2015). In particular, in the mitigation of slope failures, it is important to understand in details the surface water flow directions and runoff generated by intense rainfall, that represent one of the main causes of soil erosion (Preti et al., 2018). High-resolution topography can help in this purpose, offering details on surface morphology (Tarolli, 2014). Morphometric indicators could be calculated on DTM using specific algorithms. Some of the most important are the slope, curvature, and drainage area. Tarolli et al. (2013) introduced a methodology (futher successfully applied in other studies e.g. Tarolli et al., 2015; Pijl et al., 2019b) to identify areas with a higher susceptibility to erosion due to the accumulation of surface water flow: Relative Path Impact Index (RPII) (Eq. 1). This index considers the contributing area as a proxy of the flow path distributions, and in a logarithmic form, it emphasizes and maps areas presenting an increased drainage area because of the presence of anthropogenic features (e.g. roads or terraces).

$$\mathrm{RPII} = \ln\left(\left(A_r - A_{sm}\right)/A_{sm}\right) \tag{1}$$

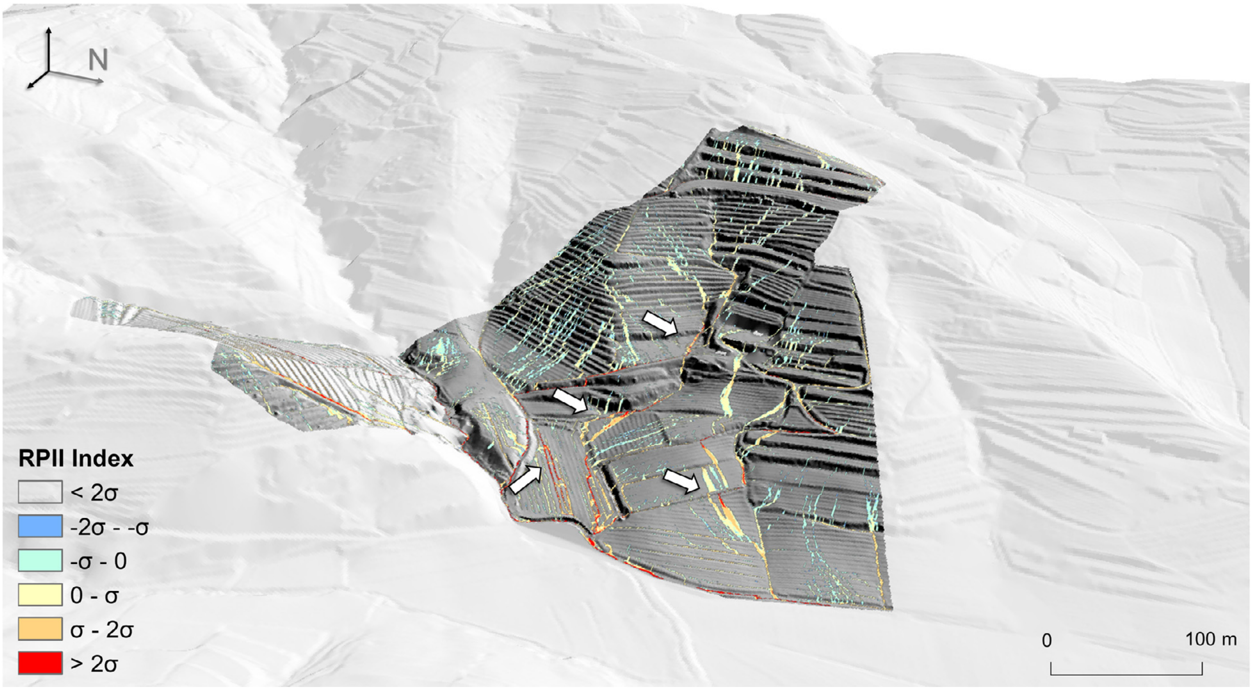

Fig. 5. 3D representation of a digital terrain model (DTM) of a terraced vineyard. In light grey, the shaded relief of DTM with 1 m resolution obtained by airborne lidar survey (dataset provided by Ministero dell'Ambiente e della Tutela del Territorio e del Mare, MATTM, Italy). In darker grey, a 0.5 DTM processed by SfM from drone images (dataset provided within SOiLUTION SYSTEM project). Arrows indicate the most likely areas prone to soil erosion according to RPII.

where A_r is the contributing area evaluated in the presence of terraces on the hillslopes, while A_{sm} is the contributing area evaluated in the absence of morphological alterations on the hillslopes. For the calculation of the drainage area, Tarolli et al. (2013) considered the D∞ flow direction algorithm (Tarboton, 1997), while to simulate the absence of roads and trail, they considered a smoothed DTM based on the quadratic approximation of the original surface (Eq. 2) as proposed by Evans (1979), solved within a local moving window, as modified by Wood (1996),

$$Z = ax^2 + by^2 + cxy + dx + ey + f \tag{2}$$

where x, y, and Z are local coordinates, and a to f are quadratic coefficients. The higher the RPII, the higher the potential runoff-induced erosion is. The general aim is to provide an innovative interpretation key of the territory, exploiting geographical maps with intuitive chromatic scales that can be easily used by a stakeholder in a multidisciplinary view (Fig. 5). Of fundamental importance, however, is the validation of the results predicted by the cartography through monitoring operations. In particular, especially during intense rainy events, a good practice is to observe the surface runoff concentrations in the field to test the suitability of the results. According to this, the use of key information obtained from the analysis of remote sensing data, such as the identification of areas potentially subject to erosion, may also be associated with in-situ observations (Robichaud et al., 2010; Wirtz et al., 2012). Such findings can offer an important added value to the results obtained by remote sensing, directing stakeholders in the implementation of highly targeted measures for agricultural and land planning. The use of new technologies in geography, such as the management of drone derived topographic data for the creation of indicators, allow to know accurately the location of the area's more prone to instability. In this way, it is possible to target interventions (such as the design of the drainage network), making them more effective in their aims and efficient in terms of environmental and economic sustainability.

5. Final Remarks

Cultivate land in high-steep slope conditions is not easy. Where this happened since ancient times, such areas have been recognized as historical heritages and cultural ecosystem services. However, such extraordinary historical, economic and landscape value is at risk because of soil loss phenomena, an increasingly threatening issue due to land abandonment, wrong mechanization practices and climate change. Geography, also thanks to the technological innovation (e.g. advanced remote sensing platforms such as lidar and UAV) that characterizes it, represents an indispensable tool for the knowledge of our territory. If used correctly, it can offer useful information to understand the physical processes affecting the Earth's surface, supporting stakeholders in finding sustainable solutions for land degradation mitigation. It could, therefore, help environmental authorities and governments to improve the guidelines for better management of agriculture lands in mountainous regions of the world. Future challenges should follow these lines with a more integrated and multidisciplinary approach to solve environmental problems, where stakeholders could really be benefited by the role of geographers.

Declaration of Competing Interest

The authors declare no conflict of interest.

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