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Remote sensing vs. field-based monitoring of agricultural terrace degradation

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ABSTRACT

The degradation of agricultural terraces is considered a major challenge to soil and water conservation in steep-slope viticulture. Although terracing is a widespread conservation practice, its sustainability is threatened by adverse climatic and man-made conditions. Previous studies have shown the impact of terrace designs on the formation of runoff pathways, causing degradation processes on terrace platforms (e.g. sheet erosion) and walls (e.g. piping, landslides, collapse). This study evaluates a remote sensing versus a field-based approach to monitor hydrological processes responsible for terrace degradation, as tested in a north-Italian vineyard. The field-based approach was based on spatially measured Soil Moisture Content (SMC) using a Time Domain Reflectometry (TDR) instrument, which clearly revealed saturation hotspots around two damaged terraces in the study area. Moreover, these zones showed a particular cross-sectional SMC profile, with the highest saturation close to the terrace platform edges. The remote sensing approach was based on aerial imagery acquired by an Unmanned Aerial Vehicle (UAV) and photogrammetric reconstruction of the vineyard geomorphology, allowing terrain-based analysis and physical erosion modelling. In this approach, simulations indicated that terrace damages could be partly explained by the formation of preferential runoff pathways caused by the terrace design. This parallel methodology allowed a comparison of the merits and limitations of either approach, as done in light of published work. The occurrence of two SMC hotspots at terrace edges (and their non-typical cross-sectional profiles) could be better understood from simulated surface flow paths. While the causal relationship between heterogeneous soil saturation and terrace instability has been previously reported in literature, the novelty of the presented study is the use of topsoil SMC as an indicator of potential damages, favouring the scalability compared to fixed, local and often intrusive terrace sub-surface experiments. Remote sensing based approaches, however, tend to offer the most time-efficient solution on larger scales, and aerial acquisition of SMC distribution could thus potentially offer a powerful integrated methodology.

1. Introduction

Viticulture in Mediterranean Europe is typically related to terraced cultivation systems on steep hillslopes, and as such, is notoriously related to high rates of soil erosion (Cerdan et al., 2010; Maetens et al., 2012; Prosdocimi, Cerdà, & Tarolli, 2016). The sustainability of terraced viticulture is therefore strongly challenged by environmental constraints, while severe land degradation has economic consequences as well (Tarolli & Straffelini, 2020). Still, it is not primarily the use of terraces that is responsible for this, but rather the general transformation of vegetated hillslopes into steep-slope agriculture (Arnáez, Lana-Renault, Lasanta, Ruiz-Flaño, & Castroviejo, 2015). Lack of maintenance is responsible for terrace failure and related land degradation (e.g. wall collapse, landslides, soil loss) under intense rainfall conditions (García-Ruiz & Lana-Renault, 2011; Lesschen, Cammeraat, & Nieman, 2008; Tarolli, Preti, & Romano, 2014), due to the ever-recurring and inherent restoration requirements of such anthropogenic structures (Arnáez et al., 2015; Stanchi, Freppaz, Agnelli, Reinsch, & Zanini, 2012). The unsuitable design of a terracing system as a whole can also cause instability of certain terrace sections due to runoff concentration

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and the formation of preferential patterns (Gallart, Llorens, & Latron, 1994; Tarolli et al., 2015). On the contrary, a well-designed terrace system has the potential to promote safe drainage as well as homogeneous distribution (Pijl, Tosoni, Roder, Sofia, & Tarolli, 2019) and delayed concentration (Perlotto & D'Agostino, 2018) of runoff. In the face of growing rainfall extremes projected for the Mediterranean basin (Gao, Pal, & Giorgi, 2006; Giorgi & Lionello, 2008; IPCC, 2014), the design of terraced vineyards are increasingly playing a decisive role in the environmental sustainability of this cultivation system. Previous studies showed that suitable terracing systems are characterised by: (i) near-horizontal platforms, oriented in such a way that runoff concentration is mostly avoided (Pijl, Reuter, Quarella, Vogel, & Tarolli, 2020); (ii) fully permeable terrace walls, to prevent piping and related macrofluxes of water and sediment (Crosta, Dal Negro, & Frattini, 2003); (iii) a well maintained drainage system parallel to the terrace walls, to capture excess runoff (Arnáez et al., 2015); and (iv) optimised ground cover such as cover crops or organic mulch, to maximise surface roughness and runoff retention (Biddoccu, Ferraris, Opsi, & Cavallo, 2016; Lesschen et al., 2008; Tarolli, Cavalli, & Masin, 2019). Clearly, individual adoption of such practices is not only (or primarily) driven by environmental consideration, but also by their costs (or missed profits). Structural measures such as dry-stone walls or drainage systems can require a significant investment (Pijl, Tosoni, et al., 2019), and in practice, vineyard designs are mostly determined by trafficability (resulting in steep cross-cutting paths and non-horizontal platforms; Ramos, Benito, & Martínez-Casasnovas, 2015), and maximised utilisation of available space (for cultivation rather than terraces or drainage systems) and available natural resources (by limiting ground cover to avoid competition Blavet et al., 2009; Marques et al., 2015). However, it can be argued that the economic sustainability of steep-slope viticulture is much in line with the rationale of environmental sustainability, characterised by soil and water conservation and homogeneous water distribution across the field. Unsuitable designs and consequent water concentration can cause high maintenance costs due to slope failure or gradual sediment outflux depleting soil fertility (Arnáez et al., 2015; García-Ruiz et al., 2015). High saturation hotspots also bring the risk of ponding and soil compaction (Capello, Biddoccu, Ferraris, Pitacco, & Cavallo, 2017; Ferrero, Usowicz, & Lipiec, 2005) and consequent soil erosion (Pijl, Barneveld, et al., 2019), whereas low saturation hotspots (i.e. due to limited local retention) can negatively affect grape yield (Medrano et al., 2015; Sofo et al., 2012). As such, to ensure sustainable steep-slope viticulture, it is crucial to monitor and understand land degradation patterns related to specific vineyard practices.

When studying the spatial occurrence (i.e. the location and causal processes) of land degradation, an often preferred approach is the use of remote sensing techniques. In particular, digital topographic information is the primary or initial variable for the mapping or modelling of degradation processes (Desprats et al., 2013), and remote sensing significantly facilitates the collection of these data at relatively large scales (single field up to entire watersheds). The rapid development of technologies such as Light Detection And Ranging (LiDAR) and Unmanned Aerial Vehicles (UAVs) over the past decades has provided high-resolution digital terrain analysis (Colomina & Molina, 2014; Tarolli, 2014; Cucchiaro et al., 2020), which is now the benchmark for spatial analysis of landslides (Jaboyedoff et al., 2012; Scaioni, Longoni, Melillo, & Papini, 2014) and other surface mass-movement and erosion processes (Eltner, Schneider, & Maas, 2016; Giordan, Hayakawa, Nex, Remondino, & Tarolli, 2018). In the context of terraced vineyard landscapes, such high-resolution topographic data has been applied either directly for the localisation or quantification of damages (Brandolini et al., 2018; Canuti, Casagli, Ermini, Fanti, & Farina, 2004; Giordan, Cignetti, Baldo, & Godone, 2017), or indirectly as an input for terrain analysis (both are hereafter referred to as "remote sensing based approach"). In the latter, high-resolution data has been shown to be useful to simulate preferential runoff pathways (Pijl, Tosoni, et al., 2019; Preti, Errico, Caruso, Dani, & Guastini, 2018;(Tarolli et al., 2015; Tarolli, Calligaro, Cazorzi, & Dalla Fontana, 2013) ,) and soil erosion patterns (Pijl, Reuter, et al., 2020) that explain observed terrace damages.

Still, in many cases, heterogeneous terrain and soil properties of terraces pose limits to the accuracy of geomorphology-based simulations (Arnáez et al., 2015; Gallart et al., 1994), particularly when surface flow is not the dominant process dictating spatial hydrology. Dry-stone wall terrace systems in particular can have a complex subsoil hydrology characterised by channelised flow and heterogeneous saturation that affect the terracing stability (Perlotto, Michelini, & D'Agostino, 2015; Preti, Guastini, et al., 2018). Simulating these hydrological, hydraulic and geotechnical processes using dedicated physical models (Camera, Apuani, & Masetti, 2014; Preti, Errico, et al., 2018) require detailed information of soil properties and terrace morphology. Monitoring at this level of detail typically depends on the installation of extensive instrumentation in the field, which is shown to be valuable to provide novel insights in terrace failure processes (Preti, Guastini, et al., 2018). However, an evident trade-off exists between accurately capturing field processes, and the scalability of methods over time and space. For certain purposes, an approach for terrace failure monitoring applicable of larger extends (emphasis on "where") is desirable over detailed and accurate understanding at smaller scale (emphasis on "why"). In this work, the simplistic assumption is tested that Soil Moisture Content (SMC) of the topsoil can be an indicator of potential terrace wall failure. As such, the "field-based approach" pursued in this study was based on spatially distributed SMC measurements using the widely accepted Time Domain Reflectometry method (TDR; Mittelbach, Lehner, & Seneviratne, 2012; Robinson, Hopmans, & Jones, 2008). This technique is a preferable option for obtaining spatially distributed measurements, due to its high response time, its non-invasive sampling method by steel rods, and insensitiveness to heterogeneous conditions of soil texture, salinity and temperature (Susha Lekshmi, Singh, & Shojaei Baghini, 2014). A few applications of TDR to analyse the spatial SMC distribution in terrace environments are reported in literature (e.g. Garcia-Estringana, Latron, Molina, & Llorens, 2013; Querejeta, Roldá, Albaladejo, & Castillo, 2000; Rabadà & Gallart, 1993; Ramos, 2016). However, previous studies focussed on temporal monitoring of a limited number of fixed measurement points, while spatial analyses were limited to transects. Instead, fully-distributed sampling and mapping of SMC may provide new and valuable insights with regards to the role of soil saturation in terrace wall instability.

In this study, the two contrasting methodologies identified above (the remote sensing approach vs. the field-based approach) were explored for their ability to explain the occurrence and location of terrace wall degradation. Both monitoring approaches were tested in a terraced vineyard in northern Italy where two examples of damages were observed: wall collapse and wall piping (Section 2.1). The field-based approach was based on spatially distributed TDR measurements in the topsoil layer (Section 2.2). The remote sensing approach was based on a UAV survey and photogrammetry for the production of high-resolution topographic data (Section 2.3), as primary input for further terrain analysis (Section 2.4). The results of either monitoring approach in reference to the observations were then separately analysed and presented (Sections 3.1 and 3.2). A cross-comparison of both approaches then led to a critical discussion of the merits and limitation of either, finally allowing for a set of recommendations for future research and practice (Section 4).

2. Material and methods

2.1. Study site

A 0.5-ha terraced vineyard was studied, located in the wine-production zone of Valpolicella, Province of Verona, northern Italy (Fig. 1a). The terraces are made up of dry-stone walls, following an ancient construction technique that is famous in this part of the world. In accordance to traditional methods and legal regulations, no concrete is used in constructing the walls to favour permeability, except partly for the above-ground section (Fig. 1c). Terraces have an average spacing of 10 m and have a west-to-east downslope orientation with an average slope of 22% (Fig. 1a). Predominant soil type found in the area is silty clay loam (USDA soil texture classification based on LUCAS soil database v1; Toth, Jones, & Montanarella, 2013). The vineyard is generally well covered by grass or cover crops throughout the seasons, with no visible evidence of bare patches except for the compacted and less-vegetated wheel tracks (Fig. 1a).

In two places, dry-stone walls in the study area showed evidence of terrace damage during March 2018 exploratory field investigations: (i) a collapsed terrace wall (Fig. 1b), and (ii) macropore piping at the surface behind a terrace wall (Fig. 1c). Whereas the latter evolved gradually over an undetermined period, the collapse (Fig. 1b) occurred around halfway March. The actual event was triggered by a moderate rainstorm (11 mm h^{-1}; Regione Veneto, 2019), although the previous 3 weeks of near-continuous rainfall (14 out of 19 being rain days, with a sum of 86 mm; Regione Veneto, 2019) and gradual soil saturation were likely the cause of terrace instability. Monthly rainfall during March 2018 was relatively high, ranking as the 3rd wettest March in 25 years, reaching two times the average for that month. However, comparable rain sums are reached during at least 6 months of an average year (during summer and autumn), and indeed, terrace instability (e.g. dry-stone wall collapse) and soil erosion are a common challenge locally, with 15% of the municipality affected by “critical soil loss rates” according to a regional survey (Regione Veneto, 2008). Terrace failure events are related to continued periods of high rainfall and peak intensity, which are relatively common in these pre-Alpine hills characterised by strong fluctuations in monthly rainfall (72 ± 45 mm) and yearly rainfall (870 ± 214 mm; (Regione Veneto, 2019). The timing of rainfall is expected to become more heterogeneous over the course of the 21st century, with local climate projections showing increased seasonality (+30−40% winter precipitation; Coppola & Giorgi, 2010; Gao et al., 2006) and growing rainstorm intensities (up to +28%; Zollo, Rillo, Bucchignani, Montesarchio, & Mercogliano, 2016).

2.2. Soil moisture field survey

Field measurements of Soil Moisture Content (SMC) were carried out during two surveys in July 2018 with different meteorological conditions. The first survey was conducted after 10 days without any precipitation prior to the survey (Regione Veneto, 2019), hereafter referred to as “dry conditions”. In contrast, the second survey was conducted one day after a 41-mm rain event (total of 51 mm over prior 10 days), hereafter referred to as “wet

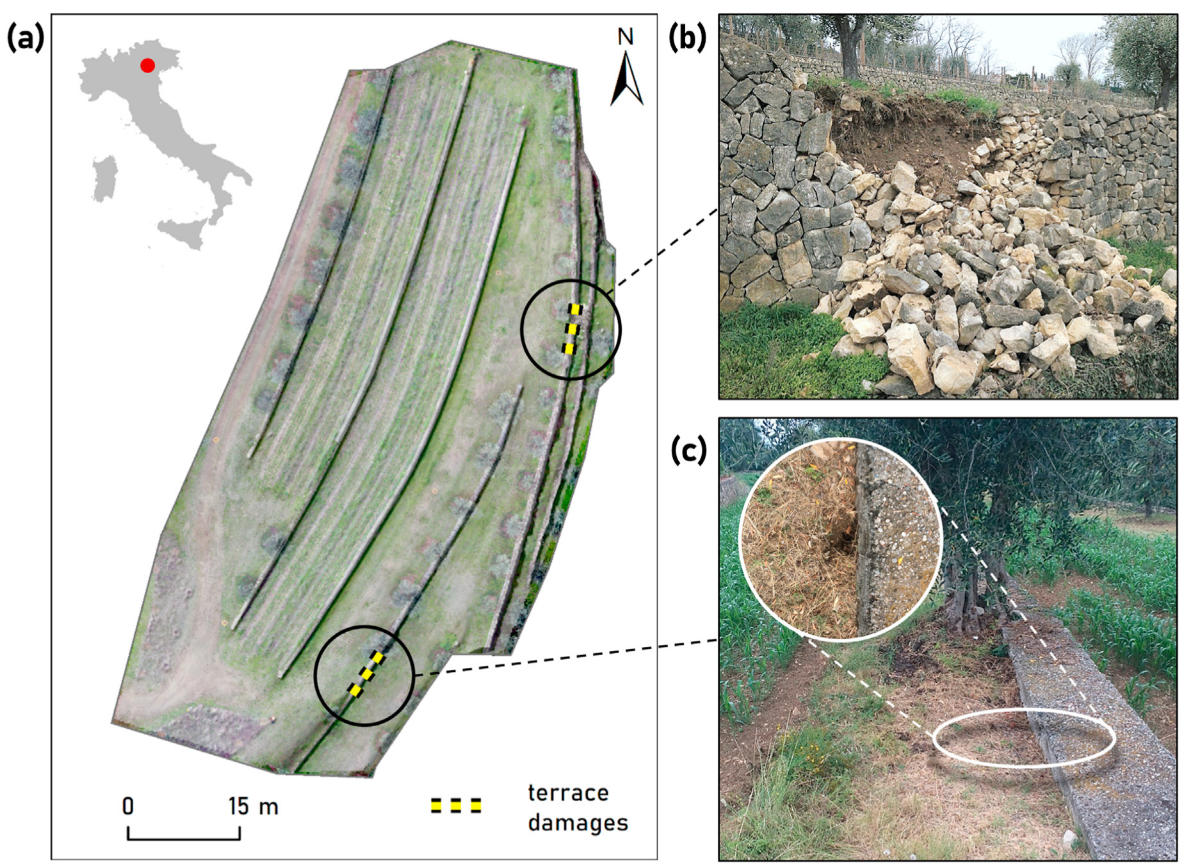

Fig. 1. Valpolicella study site with two damaged terraces indicated by yellow dashed lines (a): a wall collapse in the north-eastern sector (b), and wall piping in the southern sector (c). Photographs by T.A. Vogel (b) and E. Quarella (c).

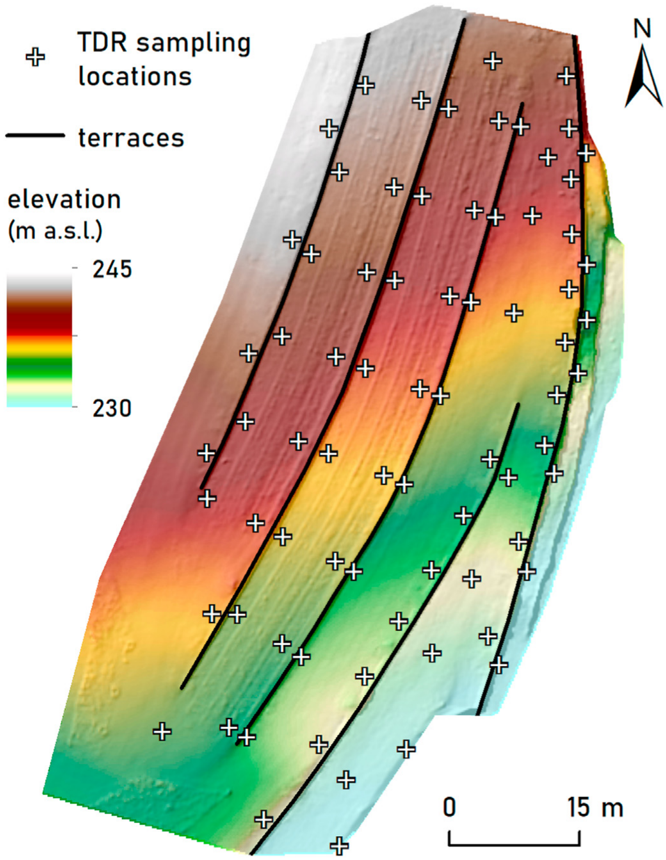

Fig. 2. Shaded Digital Terrain Model (DTM) of the study area, overlaid with the locations of TDR sampling points distributed throughout the site (white crosses).

conditions". Topsoil SMC at 7.6 cm depth was measured using a *FieldScout TDR300* (*Spectrum Technologies, Inc.*) Time-Domain Reflectometry (TDR) instrument that was pre-calibrated following the prescribed procedure (product manual; Spectrum Technologies Inc., 2009). Measurements were taken at 75 points distributed throughout the study area (Fig. 2), which were maintained the same for both surveys by way of trilateration based on fixed objects in the field (e.g. olive trees and concrete vine support poles). The placement of the points was based on a regular spread following the terrace morphology, with measurements taken relatively close to the terrace wall edge and foot. At each point, 5 data readings were taken to determine the trimmed mean SMC (i.e. the mean of the middle 3 values). Point-based SMC distribution was then interpolated using GIS software, using the "Spline with Barriers" tools to account for the artificial terrain interruptions posed by the terrace walls (Fig. 2).

2.3. Topographic remote sensing survey

A workflow of UAV-based Structure-from-Motion (SfM) photogrammetry was used to reconstruct a detailed digital model of the vineyard geomorphology. During March 2018, a remote sensing survey was carried out using a *DJI Mavic Pro* micro-drone mounted with an optical camera (12.3 MP lens, 4.7 mm focal length) to take 91 aerial photographs of the study area with >75% overlap. Images were transformed into a 3D point cloud using *Agisoft PhotoScan* (v1.2.4) SfM software, calibrated using 10 DGPS ground reference points measured in the field using a *TopCon HyperV* device. The TERRA algorithm (Pijl, Bailly, et al., 2020) was used to automatically remove any above-ground objects from the digital model while preserving terrace morphology, resulting in a high-accuracy (0.05 m) and high-resolution (0.2 m) Digital Terrain Model (DTM; Fig. 2).

2.4. GIS applications based on remote sensing data

Two distinctive terrain analyses were carried out based on remote sensing data to understand the locations of terrace damages. The first was the basic geomorphologic Topographic Wetness Index (TWI) computed from the high-resolution DTM (Section 2.3) and derivatives. It was developed by Beven and Kirkby (1979) as part of the hydrologic TOPMODEL and indicates potential soil wetness, as correlated positively to local upstream area a and negatively to local slope value $tan(b)$, according to $ln(a/tan(b))$. For this study, the index was calculated using *SAGA* (v2.3.2) GIS software in default setting. The second analysis was based on the more complex physical SIMulated Water Erosion model (SIMWE) that has been applied using standard parameter values available in literature, in order to maintain a distinction with the field-based approach (i.e. all firsthand information was remotely sensed). SIMWE was developed by Mitas and Mitasova (1998) based on the Water Erosion Prediction Project model (WEPP; Flanagan & Nearing, 1995), but providing a full spatial distribution suitable for erosion modelling in complex terrain using high-resolution DTMs. It consists of a hydrologic and a soil erosion component, integrated in *GRASS* (v7.4.1) GIS software as tools *r.sim.water* and *r.sim.sediment*, respectively (Neteler & Mitasova, 2008). The former is based on a bivariate form of Saint-Venant equations that combines the continuity relation of the water flow with the momentum conservation equation. The latter is based on the continuity relation of sediment mass describing sediment transport by overland flow. Model input data was solely based on remote sensing data and auxiliary information from databases. Topographic data consisted of the high-resolution DTM (Section 2.3) and its x- and y-derivatives computed by *GRASS* tool *r.slope.aspect* (Hofierka, Mitasova, & Neteler, 2009). Rainfall data was available from measurements at a nearby meteorological station, and simulations were based on peak rainfall of 82 mm h^{-1} recorded in September 2018 (Regione Regione Veneto, 2019). During the preliminary phase of this research, an additional set of high-intensity rainfall input values (ranging between 100 and 300 mm h^{-1}) was used to test the sensitivity of simulated water and sediments flow under even more severe rainstorm conditions. Preliminary results showed that mostly the rate of surface flow was affected, while the spatial flow patterns remained largely unchanged (with severe runoff generation occurring in any simulation, including the lowest input rainfall). These arbitrary simulations were not included here, as the scope of this methodological approach was to locate the spatial preferential pathways, rather than to estimate the magnitude of surface fluxes, and these were sufficiently evident with the recorded rainfall event of 82 mm h^{-1}. Saturated hydraulic conductivity was set to 15 mm h^{-1} based on an average of previous measurements in a nearby vineyard (Pijl, Reuter, et al., 2020). Manning's roughness coefficient was set to 0.035 based on classifications by Chow (1959) for grassland (i.e. the predominant land cover in the study area). Finally, soil parameters detachment capacity coefficient, transport capacity coefficient and critical shear stress were set to 0.001 s, 0.001 s m^{-1} and 0.5 Pa, respectively, in accordance to previous applications by developers (Mitasova, Barton, Ullah, Hofierka, & Harmon, 2013) and other researchers (Fernandes et al., 2017; Pijl, Reuter, et al., 2020). The output of the two GIS approaches consisted of a topographic soil wetness map (TWI) and simulated water discharge and sediment flux maps (SIMWE). Their utility for locating, explaining and potentially predicting terrace damages was evaluated and elaborated in the following chapter.

3. Results

3.1. Field-measured soil moisture content and terrace damages

Interpolated TDR measurements of Soil Moisture Content (SMC) are shown in Fig. 3. The overall difference in SMC magnitude between the dry (Fig. 3a) and wet conditions (Fig. 3b) is clearly visible over the majority of the vineyard. This is reflected by mean SMC values, with the wet state (μ_{wet} = 31.9%) being roughly two times wetter than the dry state (μ_{dry} = 15.6%). Respective standard deviations for both conditions have comparable magnitudes (σ_{wet} = 8.3% and σ_{dry} = 6.9%), although when taking into account the different mean magnitudes, this indicates a stronger relative spread of dry-state SMC. Histograms furthermore show that dry-state SMC has a stronger skew than wet-state SMC (Fig. 4a), indicating that the majority of measurements are eccentric and the effect of a minority of extreme values. These extreme values are found on the right-hand tail of the distribution (i.e. a positive skew), and reflect the hotspots of high SMC that can clearly be identified in the dry-state SMC measurements (Fig. 3a). The SMC distributions in Fig. 4 thus suggest that dry-state SMC measurements could be more useful in identifying high-value hotspots than measurements in wet conditions.

It is worth noting that the two highest hotspots are found in direct vicinity to the two damaged zones. Around the north-eastern damaged terrace (Fig. 3a and b, yellow dashes), SMC in dry- and wet state respectively exceeds 55% and 65% on the platform right above the damaged terrace wall (any expected causal relationships are elaborated in Section 4.1). This high-SMC zone also stands out by its large extent, exceeding 10 m of upslope range from the upper terrace edge. Around the southern damaged terrace (Fig. 3a and b, yellow dashes), a hotspot with the second-highest SMC values are found, equal to roughly 40% and 50%, respectively. However, in dry conditions the highest values are found at the bottom of the damaged terrace wall rather than on top (although SMC on top was still slightly higher than its surroundings).

In order to understand the typical SMC distribution along a cross-sectional profile of the terraces, a downslope transect was drawn through a representative section in the centre of the vineyard, ending in the location of wall collapse (dashed arrow in Fig. 3a and b). SMC values in wet and dry conditions were extracted across this transect and plotted (Fig. 3c and d, respectively) including the transect DTM profile (black dashed lines). Two different patterns can be recognised in the transect profiles, visible on two different scales:

i. On the field scale, SMC is negatively related to elevation and thus increases in downslope direction (left-to-right in Fig. 3c and d). Each subsequent downhill terrain drop (i.e. terrace wall) corresponds to an upwards jump in SMC, with the highest saturation found at the lowest terrace.
ii On the single-terrace scale, SMC typically shows a gradual drop across the width of a terrace bank in downslope direction, i.e. at a given terrace, the highest saturation is found at the foot of the wall rather than on top (Fig. 3c, transect section 5-18 m, indicated by a blue arrow). This pattern recurs throughout dry and wet conditions at almost all terrace cross-sections (Fig. 3c and d), and could well be understood from the draining properties of terrace walls (and represents a typical distribution reported in literature, Section 4.1). However, a non-typical single-terrace SMC profile is found in only two zones across the vineyard, accurately corresponding to the damaged terrace walls. In either dry or wet conditions, SMC profiles at these two banks are "inverse": single-terrace soil wetness *increases* in downslope direction, peaking very close to the damaged walls (Fig. 3c and d, transect section 28-40 m, indicated by a red arrow). Although more high-SMC hotspots can be recognised in the terraced vineyard, these two zones are showing the clearest examples of

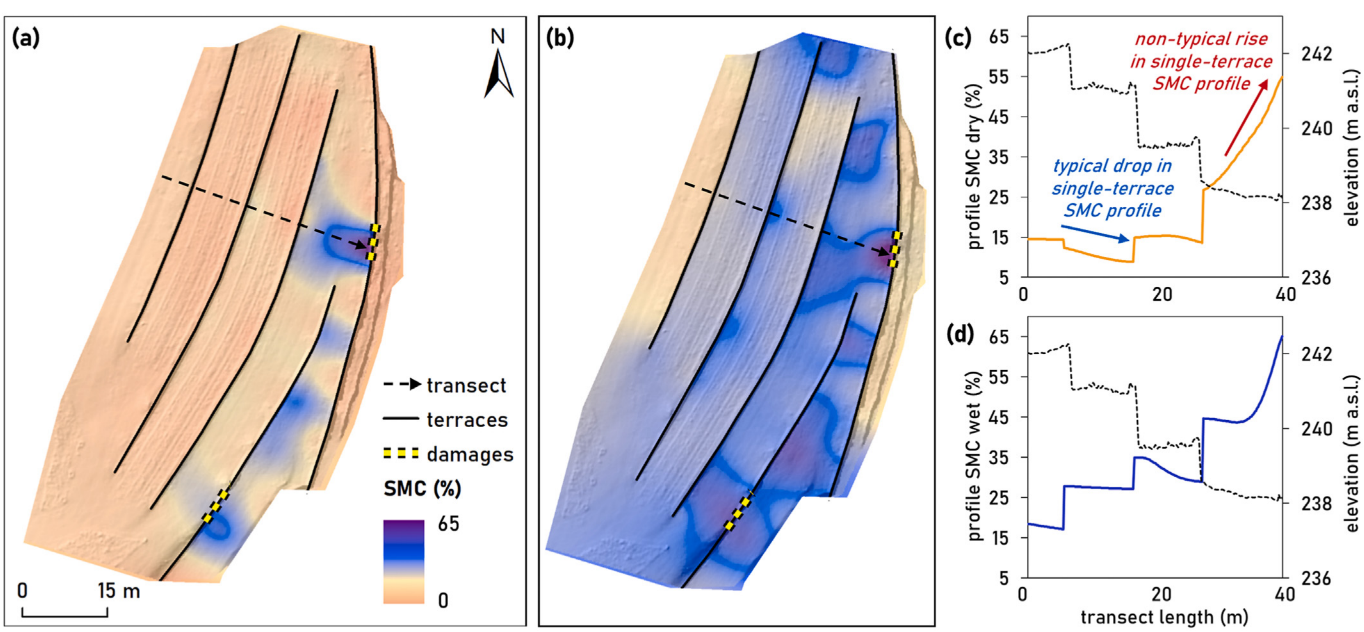

Fig. 3. Soil Moisture Content (SMC) distribution in dry (a) and wet (b) conditions, showing higher saturation in the two zones of terrace damages (yellow dashes) than the rest of the vineyard. On the field scale (entire transect), SMC profiles increase in downslope direction, i.e. negatively related to elevation (black dashed lines), in both dry (c, orange line) and wet conditions (d, blue line). On the single-terrace scale, the SMC profile typically drops in downslope direction due to drainage by walls (e.g. transect section 5-18 m, blue arrow). Strikingly, an inverse single-terrace SMC profile is found at the damaged lowest terrace (transect section 28-40 m, red arrow), where SMC rises in downslope direction and peaks at the damaged walls (yellow dashes).

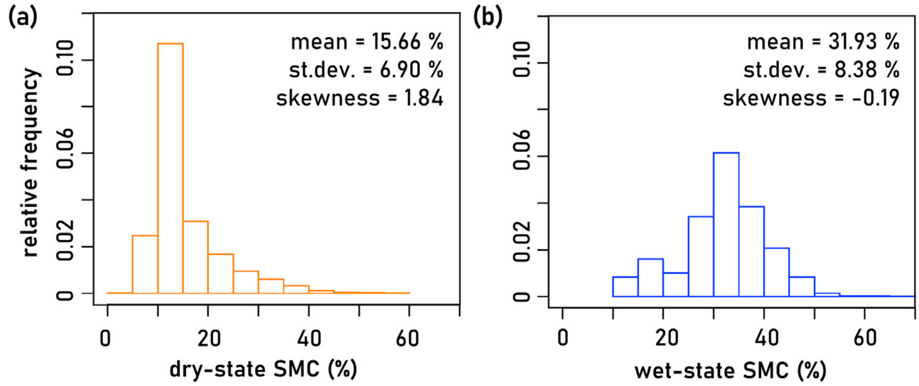

Fig. 4. Histograms showing the relative frequency of dry-state (a) and wet-state (b) SMC values. Whereas mean SMC is roughly two times higher in the wet state than the dry state, the standard deviations are of similar magnitude. Dry-state SMC shows a stronger positive skew as compared to a weaker negative skew in wet-state SMC, emphasising the relative sparseness of high-SMC hotspots in the first.

high saturation near the edge of a terrace platform, leading to insights further discussed in Section 4.1.

3.2. Remote sensing-based GIS applications and terrace damages

The Topographic Wetness Index (TWI) shows clear preferential pathways of runoff throughout the vineyard (Fig. 5a). Two main corridors can be recognised that lead to the lowest terrace: a major flow in the south-western sector and another major flow in the north-eastern sector (blue arrows). The former is most severe, as it collects most of the lateral runoff from the terraces that have a north-to-south downslope orientation. It eventually reaches the lowest terrace wall exactly in the damaged part where wall piping occurred. TWI values are particularly high around the southern damaged terrace (Fig. 5a, dark blue colours), with a pixelar maximum value of 13.6 (equal to 5.2 times standard deviation σ_{TWI}) as compared to an area mean μ_{TWI} of 2.4. Similarly, the study area highest values of simulated water discharge (Q) and sediment flux (SF) are found exactly at the piping location (purple colour in Fig. 5b; deep red colours in Fig. 5c), with pixelar maxima of 0.103 $m^3\ s^{-1}$ (54.2 * σ_Q) and 0.798 $kg\ m^{-1}\ s^{-1}$ (53.2 * σ_{SF}), compared to area means of $\mu_Q = 0.0004\ m^3\ s^{-1}$ and $\mu_{SF} = 0.005\ kg\ m^{-1}\ s^{-1}$.

The major flow pattern to the north-east (Fig. 5a), instead, seems to be shorter and runs southwards past the collapsed terrace wall by a few meters. Nonetheless, a diffuse pattern of relatively high TWI values is visible at the terrace bank above the collapse (Fig. 5a, dark blue colours). This indicates the presence of a locally horizontal surface (i.e. low $tan(b)$), that combined with a large contributing area (i.e. high a) results in widespread high TWI values, with a maximum of 9.8 (equal to 3.7 * σ_{TWI}). A similar high-TWI pattern is found across the remainder of the lower (easternmost) terrace, although with lower magnitudes than that found around the collapsed wall. With regards to minor surface flow patterns (Fig. 5; blue arrows), all three simulations show the formation of parallel surface flows on the upper (i.e. westernmost) three terraces. Spatial analysis revealed that these are related to the presence of wheel tracks caused by repeated passage of machinery in the vineyard inter-rows. Thanks to the high resolution of the input data, the slightly low-lying and compressed tracks are well

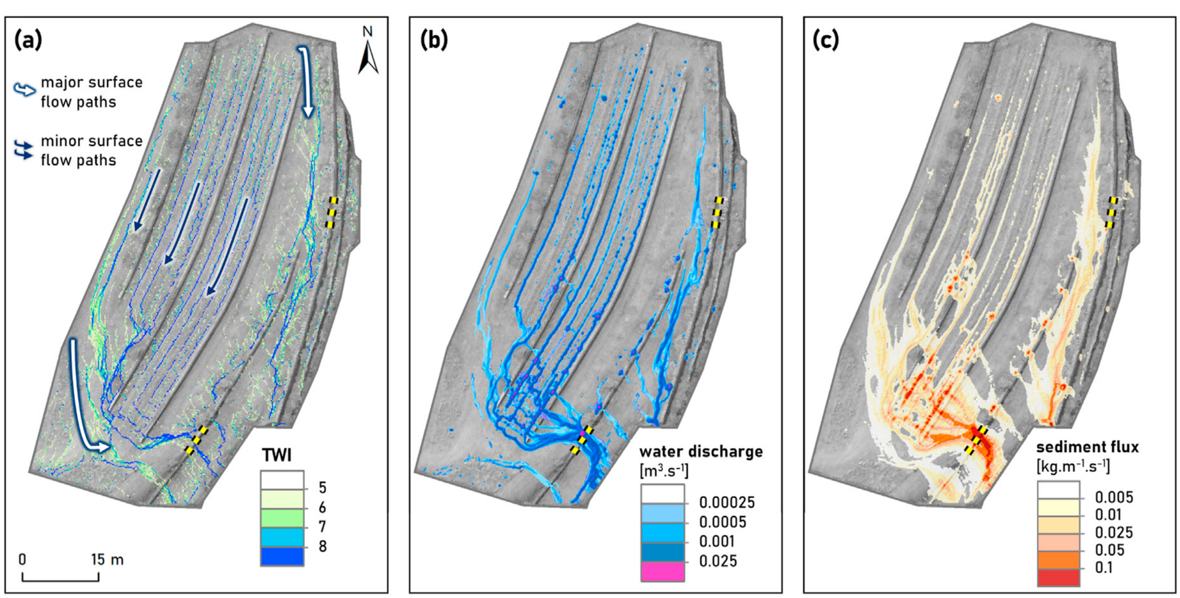

Fig. 5. Spatial distributions of TWI (a) and SIMWE overland water discharge (b) and sediment flux (c) displayed on a greyscale orthophoto. Indicated are the two locations of terrace damages (yellow dashes) and the minor and major fluxes over the surface (blue arrows).

captured as micro-topography. The impact on preferential surface flow pathways is evident from the patterns in TWI and simulated discharge and sediment flux, running in north-to-south direction before joining together into a concentrated flow path leading to the southern damaged terrace wall.

4. Discussion and recommendations

4.1. Merits and limitations of the field-based approach

Field-measured spatial SMC corresponded particularly well to the *location* of observed terrace instability, with the wettest terrace soils shown to be in direct vicinity of the two observed terrace damages. Dry-state measurements provided the greatest contrast between these two extraordinarily wet zones and their drier surroundings. But perhaps most strikingly was the cross-sectional SMC of the two terrace platforms above the damaged walls, showing an “inverse” profile with the highest values near the edge. Not only does this contrast the typical profile found in the remainder of this study area, but it also differs from the expected processes in terraced vineyards as reported in literature. Previous hydrogeological studies on Mediterranean dry-stone wall terraces indicated that soil saturation is expected to be higher at the foot of the terrace wall than on the platform edge (Arnáez et al., 2015; Gallart et al., 1994, 1997; Llorens, Latron, & Gallart, 1992), as is the case in the majority of the study area presented here.

The exceptional patterns found in this study led to a novel hypothesis: high topsoil SMC close to a terrace edge with respect to upslope surrounding values (i.e. an “inverse” SMC profile) could be related to the risk of terrace damage in the form of structural instability (i.e. wall collapse) or as macro-pore flux of runoff and sediments (i.e. wall piping). One evident cause for such a profile could be the locally high upstream area, as exemplified in this study by the parallel methodology (e.g. Fig. 5). This hypothesis is roughly in line with previous studies that exemplified how terrace wall collapse was related to a perched groundwater table or increased pore water pressure at the terrace edge (Camera et al., 2014; Crosta et al., 2003; Preti, Guastini, et al., 2018). However, the novelty of this hypothesis is the fact that potential terrace failure could be detected from the topsoil SMC (physically and symbolically in between the surface and sub-surface, or “quasi-surface”), which favours scalability and could serve as an early-warning indicator (further discussed in Section 4.3). A clear limitation is the absence of pre-event data (e.g. SMC distribution before the terrace damages), which would be crucial to confirm or refute this hypothesis. Without this information, it is unclear to what extent the damage themselves contributed to these SMC hotspots (e.g. by locally creating preferential flow or higher conductance). Nonetheless, there are valuable indications that high SMC represents the cause of terrace failure (not solely the effect): (i) the spatial extent of the two hotspots, reaching up to 10 m in upslope direction from the damaged terrace; and (ii) the locally high flow concentration (cross-confirmed through the remote sensing methodology). This suggests that the initial formation of relatively large SMC hotspots were related to concentrated runoff flow, initiating the terrace damages, and presumably aggravating the degree of saturation further as a consequence. Future exploration of this hypothesis based on multi-temporal monitoring of pre- and post-event hydrological states are needed and strongly encouraged, in order to explore the potential for early-warning and prevention.

Notably, the magnitude of high-SMC hotspots in dry conditions (Fig. 3a) remain remarkably high after 10 days without rainfall. Apart from the two zones previously discussed, a few additional saturation zones are visible across the easternmost terrace platform (Fig. 3a). While these hotspots do not necessarily show an inverse profile, their vicinity to the terrace edge may cause additional instability in the future. Interestingly, all of these high-SMC zones closely correspond to relatively high potential runoff accumulation (Fig. 5) and, as such, illustrate a strong “memory-effect”. Nonetheless, an evident limitation of the field-based methodology (i.e. without the knowledge of the parallel remote sensing approach) is the lack of understanding why potentially harmful SMC hotspots occur in certain locations.

4.2. Merits and limitations of the remote sensing approach

The remote sensing methodology proved to be most useful for understanding the *spatial patterns* causing potential terrace instability, i.e. by formation of preferential runoff pathways and their accumulation in critical points. A benefit of this approach is the quantification of simulated water and sediment fluxes. Indeed, the highest rates of TWI, water discharge and sediment flux are related to a critical point in the area (i.e. the example of wall piping). The merit of a geomorphological approach for the purpose of identifying potential runoff accumulation related to the terracing system design has been illustrated in several previous studies (Pijl, Reuter, et al., 2020; Preti, Guastini, et al., 2018; Tarolli et al., 2015; Tarolli & Straffelini, 2020). However, this approach is mostly valid when runoff is the dominant hydrological process or erosive agent. A purely remote sensing based approach falls short when slopes are limited and subsurface processes (i.e. infiltration or lateral flow) become more relevant, due to process simplifications and assumptions of spatial heterogeneity. This limitation is exemplified here by the collapsed terrace wall: although water concentration is simulated to be rather high across the easternmost terrace, the exact location of the damaged terrace is not clearly indicated (Fig. 5, upper yellow dashed lines).

4.3. Final remarks

For future terrace monitoring (either for management or research purposes), the recommended experimental set-up depends on the specific process and scale of interest. Field-measured SMC distribution may provide a reliable indication of dry-stone wall terraces under risk of degradation (Section 4.1), which is highly valuable for timely maintenance or structural redesign to prevent large-scale damages, although on the local scale of a single terrace section. In contrast, the remote sensing approach is most suitable for understanding hillslope-scale surface processes, such as the formation of preferential pathways. Although this information can be related to terrace damages, it is not always a reliable predictor for local instability (Section 4.2), and is therefore most suitable for larger-scale interventions such as the design of a terracing system or a drainage system on the vineyard-scale, as illustrated by previous research (Pijl, Tosoni, et al., 2019). An integrated understanding and modelling of subsoil hydrology (as well illustrated by Preti, Errico, et al., 2018) are often related to extensive instrumentation (Preti, Guastini, et al., 2018) and is therefore limited in scale, hence a relatively rapid and non-invasive topsoil survey such as TDR could be a suitable trade-off of informative quality and spatial coverage. Scalability could potentially be further improved by remote sensing-based soil moisture surveying. The use of UAV-borne thermal imagery to estimate spatial soil moisture is increasingly being explored, although feasibility in vineyards may be challenging due to heterogeneous terrain conditions and vegetative cover (Acevo-Herrera et al., 2010; Turner, Lucieer, & Watson, 2011). Potentially, opportunities may lie with the more successful UAV-based monitoring of plant-water response (Briglia et al., 2019; Fernández, 2017) to provide an *in vivo* proxy for the spatial distribution of soil water.

Finally, this case study clearly exemplifies the impact of the terrace system design on the challenge of wall failure and soil erosion. Although the southwards inclination of the terrace platforms is quite limited, their slight diagonal design allows for the formation of preferential pathways (facilitated by compacted wheel tracks in the same direction), eventually causing a destructive accumulation of water. Although the effective occurrence of wall collapse or piping results from a complex interplay of subsurface hydrogeological processes, it is safe to state that a more evenly-distributed retention of water across the vineyard would lower the risk of terrace failure.

5. Conclusions

The occurrence of two terrace damages in a vineyard (wall collapse and piping) were tested based on two distinct approaches: a field-based survey of spatial Soil Moisture Content (SMC) vs. a remote sensing survey allowing computation of the Topographic Wetness Index (TWI) and simulations by the SIMulated Water Erosion (SIMWE). The spatial distribution of field-measured SMC was heterogeneous, showing two SMC hotspots around the damaged terraces. A closer inspection of SMC distribution on these two specific terraces revealed a non-typical SMC cross-sectional profile with higher soil saturation above the terrace wall than the upstream surroundings (which was unique in our dataset and opposite to the typical profile). It is hypothesised that this particular pattern may be an accurate predictor of terraces under risk, and the field-based approach is therefore deemed valuable for localisation purposes. The remote sensing approach, on the other hand, showed clear preferential pathways of overland flows of water and sediment. The most apparent runoff pattern could be directly linked with the location of the terrace damaged by piping, although the second location (wall collapse) was not as clearly indicated by the flow patterns. This geomorphology-based approach is therefore not as conclusive about the location of damages, however, it provides unique insights about the cause of damages. Both approaches have a certain utility for detecting, predicting, and resolving terrace wall damages, although the optimal operational scale is different. Field measurements, including those conducted in a relatively dry soil state, indicate particular single terrace zones that require maintenance or structural redesign, whereas remote sensing-based digital terrain analysis are more suitable for a redesign on the vineyard scale. Moreover, the latter can be up-scaled to a larger extent (e.g. an entire hillslope or sub-watershed) with much less additional effort than the former. Understanding the processes underlying terrace degradation is a crucial part of maintaining the soil and water conservation functions, and thus the sustainability of this conservation practice (both from environmental and economic perspectives). This methodological case study could improve the effectiveness of future surveys for practical or scientific purposes, and contribute to sustainable designs of terraced vineyards.

Declarations of competing interest

None.

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