Received: 28 June 2021 | Revised: 15 November 2021 | Accepted: 3 December 2021

DOI: 10.1002/ldr.4170

RESEARCH ARTICLE

WILEY

Soil and water conservation in terraced and non-terraced cultivations: an extensive comparison of 50 vineyards

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Funding information
University of Padova research project "ViTE – Vineyard terraced landscapes: understanding the environmental constraints to improve sustainable management", Grant/Award Number: (DALL_FINAC_P14_02); Project SOiLUTION SYSTEM "Innovative solutions for soil erosion risk mitigation and a better management of vineyards in hilly and mountain landscapes" (*Programma di Sviluppo Rurale per il Veneto 2014-2020)*

Abstract

Understanding the soil and water conservation (SWC) impact of steep-slope agricultural practices (e.g. terraces) has arguably never been more relevant than today, in the face of widespread intensifying rainfall conditions. In Italy, a diverse mosaic of terraced and non-terraced cultivation systems have historically developed from local traditions and more recently from the introduction of machinery. Previous studies suggested that each type of vineyard configuration is characterised by a specific set of soil degradation patterns. However, an extensive analysis of SWC impacts by different vineyard configurations is missing, while this is crucial for providing robust guidelines for future-proof viticulture. Here, we provide a unique extensive comparison of SWC in 50 vineyards, consisting of 10 sites of 5 distinct practices: slope-wise cultivation (SC), contour cultivation (CC), contour terracing (CT), broad-base terracing (BT) and oblique terracing (OT). A big-data analysis approach of physical erosion modelling based on high-resolution LiDAR data is performed, while four predefined SWC indicators are systematically analysed and statistically quantified. Regular contour terracing (CT) ranked best across all indicators, reflecting a good combination of flow interception and homogeneous distribution of runoff and sediment under intense rainfall conditions. The least SWC-effective practices (SC, CC, and OT) were related to vineyards optimised for trafficability by access roads or uninterrupted inter-row paths, which created high upstream-downstream connectivity and are thus prone to flow accumulation. The novel large-scale approach of this study offers a robust comparison of SWC impacts under intense rainstorms, which is becoming increasingly relevant for the sustainable future management of such landscapes.

KEYWORDS
big-data analysis, remote sensing, soil and water conservation, soil erosion, terracing

1 | INTRODUCTION

Land degradation is an increasingly urgent global challenge that affects food production, economic activities, and ecosystem services such as landscape value (Borrelli et al., 2017; Montanarella, 2015). Especially in cultural landscapes, such as the particular agro-ecosystems that evolved in many hilly and mountainous environments worldwide (Tarolli & Straffelini, 2020; Wei et al., 2016), the loss of soil in quantitative and qualitative terms could have severe impacts on the future longevity and resilience of these cultivation systems (Arnáez et al., 2015; Brandolini et al., 2018b; Tarolli et al., 2021). One of the key drivers of erosion is climate change, resulting in higher-intensity rainfall events often interspersed with drought (IPCC, 2014; Panagos et al., 2015). In Mediterranean Europe, home to centuries-old cultural landscapes, this trend has been witnessed in the near past (Diodato et al., 2011; Sofia et al., 2017), and is projected to continue in the future (Coppola & Giorgi, 2010; Gao, Pal, & Giorgi, 2006; IPCC, 2014).

A recent example of a devastating meteorological event (that caught the attention of the Natural Hazards Division of the European Geosciences Union[1]) occurred in northern Italy on the 29th of August 2020. The pre-alpine hills of the Soave wine production zone in the Veneto region (northern Italy) saw the development of a supercell, causing a downburst and high-intensity thunderstorms with recorded peak rainfall of 182 mm hr^{-1} in a 5-min interval (ARPAV, 2020). The renowned cultural vineyard landscapes found in this part of Italy suffered the consequences of this event, with blasting winds uprooting vine plants and heavy rainfall causing overland flow and rill formation (Figure 1). In the face of these conditions, soil and water conservation (SWC) measures become increasingly relevant (Biddoccu et al., 2016; Tarolli & Straffelini, 2020).

Historically, a diverse mosaic of terraced and non-terraced vineyard configurations have evolved in northern Italy, each system characterised by different SWC impacts and processes of soil degradation (Pijl et al., 2020). These various vineyard cultivation practices result from many factors, including traditional construction methods and more recently the introduction of machinery (Agnoletti et al., 2011; Bonardi & Varotto, 2016; Stanchi et al., 2012). In order to provide an environmental impact perspective to future land management planning for this landscape, it is important to study the SWC impact of different vineyard configurations. Previous studies determined the impacts of different terracing types following a field-measurements approach. For example, Martínez-Casasnovas & Ramos (2009) reported an average soil depth reduction of 35% in 394 site observations due to the removal of traditional terraces for introducing mechanised vineyards. Erosion models offer a powerful tool for understanding spatial processes of water and soil movement and allow for scenario analysis under simulated conditions (García-Ruiz et al., 2015; Mitasova et al., 2013). The potential of modelling is growing thanks to the continuous growth of computational power and availability of high-resolution geospatial data (Eltner et al., 2016; Cucchiaro et al., 2020), for example, as illustrated in previous studies on terrace failure (Giordan et al., 2017; Pijl et al., 2021; Tarolli et al., 2021) or the impact of vineyard management (Brandolini et al., 2018a; Marques et al., 2007; Pijl et al., 2019a; Ramos & Porta, 1997). In a recent study, the physical erosion model SIMWE was applied for a detailed spatial analysis of erosion and runoff processes occurring in three different terraced and non-terraced cultivation systems in northern Italy (Pijl et al., 2020). This work provided unique insights into the impact of vineyard configuration on surface processes, such as the formation of critical preferential pathways on terraces, challenging their structural stability. Despite the novelty and relevance of this previous work, its representativeness could be limited due to the low number of vineyards analysed (1 site for each of the 3 practices). In order to propose an urgently needed guideline for sustainable viticulture characterised by future-proof SWC functioning, a more extensive analysis is needed to minimise site-specific processes and findings (Pijl et al., 2020; Tarolli & Straffelini, 2020).

In this work, we provide a massive comparison of 50 vineyards with 5 terraced and non-terraced cultivation practices typically found in northern Italy, in order to acquire a robust understanding of the SWC effects under each practice. We followed a big-data approach of LiDAR topographic data, serving as input for high-resolution physical erosion simulations, which were systematically analysed and tested for statistically significant differences. The presented outcomes not only offer validation of previous findings but also provide novel insights into the impact and sustainability of these cultivation practices, through the definition of four different SWC indicators and scenario analysis.

FIGURE 1 Devastating impact on vineyard plants (left) and soils (right) by the recent downburst that occurred on the 29th August 2020 in the Soave wine production zone in Veneto, northern Italy (photographs by P. Tarolli) [Colour figure can be viewed at wileyonlinelibrary.com]

2 | MATERIALS & METHODS

2.1 | The vineyard landscape of northern Italy

Our study focuses on a typical wine production zone located in the Veneto region of northern Italy. This century-old vineyard landscape not only reflects the cultural heritage but is also known for its premium wine produced through the so-called 'heroic viticulture' characterised by manual cultivation on terraced slopes (Tarolli & Straffelini, 2020). However, machinery is increasingly being adopted in viticulture, leading to a range of different vineyard cultivation systems (Agnoletti et al., 2011; Geronta, Ferrario & Turato, 2018). The five distinct types of hillslope configurations recognised in this vineyard landscape (Figure 2) are defined here as:

1. **Slope-wise cultivation** (hereafter SC): known as 'rittochino' in Italian, this practice is characterised by a uniform hillslope without any use of terraces. Vine-rows are cultivated in a slope-wise uphill-to-downhill orientation (i.e., perpendicular to the contour) with a typical spacing of roughly 2 m to allow tractor passages through each inter-row. Nowadays, this practice is increasingly common in steep-slope viticulture, as it is relatively easy to construct and maintain by machinery, and it optimises the hillslope space in terms of planting density. Access paths are generally found along the contours above and below the cultivated slope.
2. **Contour cultivation** (hereafter CC): this practice, known as 'girapoggio' in Italian, is characterised by the lack of any terraces, similar to SC. In fact, the two practices are quite similar in terms of hillslope geomorphology, except that the vine-rows are oriented along the slope contours. This limits trafficability on steeper slopes (due to a lateral tractor inclination), but it could slightly benefit flow interception due to the subtle earth bunds caused by the roots of the vines. Access paths are generally found on the sides of the CC vineyard, perpendicular to the slope.
3. **Contour terracing** (hereafter CT): known as 'ciglionamento' in Italian, this is the most regular type of terracing by use of inclined earth banks. These terraces are typically constructed by machinery with a relatively narrow width, allowing one or two vine-rows with inter-row spacing suitable for tractor passage. The high relative density of terraces prevents the need for long or steep risers (as compared to broad-base terracing below), however, bench instability and subsequent mass movement could occur with this

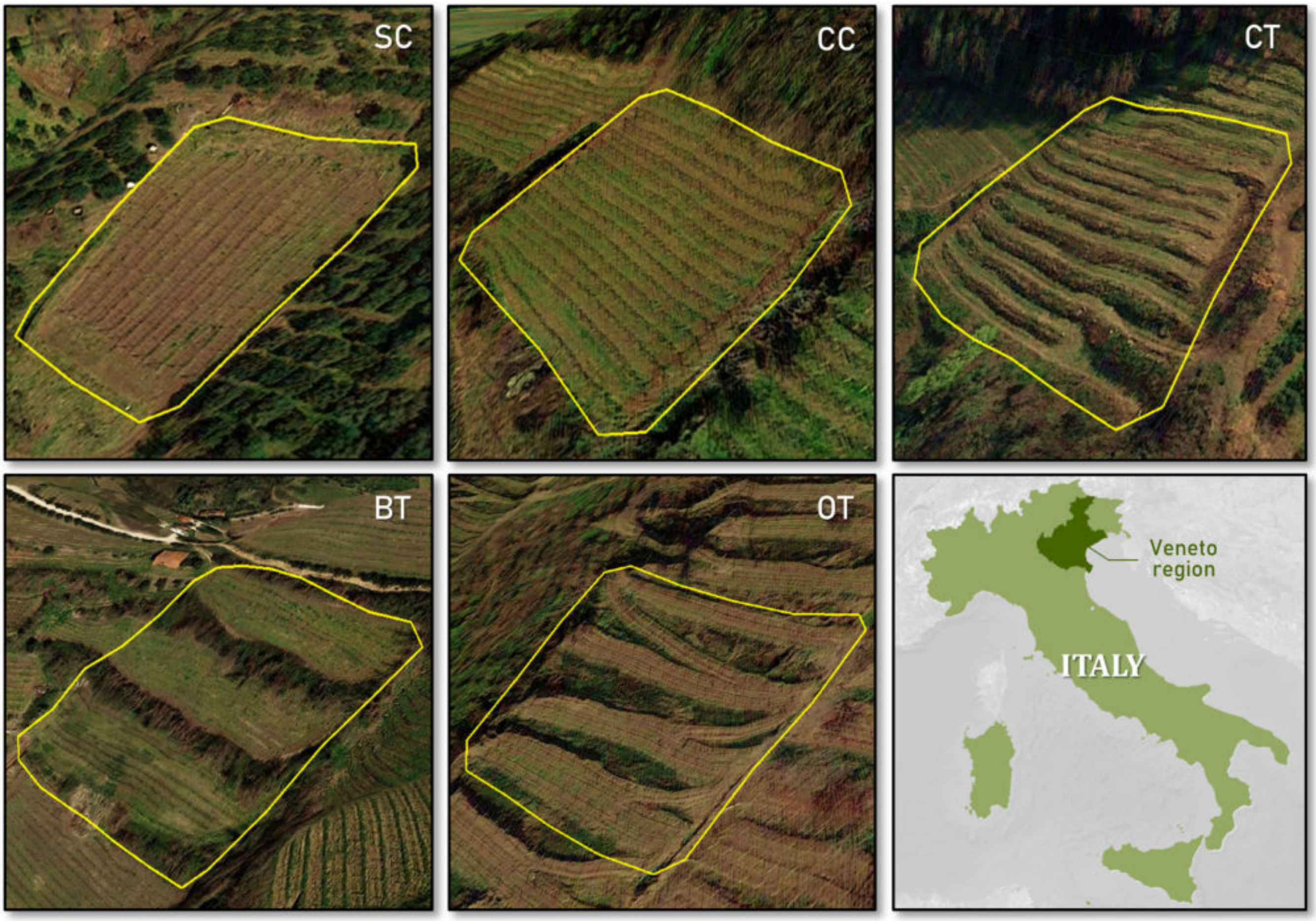

FIGURE 2 Five distinct vineyard hillslope practices found in the Veneto region (right-bottom) were analysed in this work: Slope-wise cultivation (SC), contour cultivation (CC), contour terracing (CT), broad-base terracing (BT), and oblique terracing (OT) [Colour figure can be viewed at wileyonlinelibrary.com]

hillslope configuration. Access paths are generally found on the sides of the CT vineyard, perpendicular to the slope.

4. **Broad-base terracing** (hereafter BT): this practice can be considered a mixture of CT and CC, with broad contour terrace platforms (constructed using earth banks as in CT, but taller) on which vine-rows are cultivated along the contour (sometimes slightly sloping as in CC). For the scope of this work, we defined BT by a terrace platform width of >7 m and <20 m (equalling 3 to 7 vine-rows). With narrower platform widths, vineyards are considered as CT, while platforms above this range are considered separate vineyards under the CC practice. The broad benches of BT are favourable for the optimisation of cultivated space, however, the taller or steeper risers are susceptible to instability mass movements. Access paths in BT are found on the sides of the vineyard, similar to CT and CC.
5. **Oblique terracing** (hereafter OT): this particular practice, known as 'ripiani raccordati' in Italian, is characterised by a relatively rare configuration of terraces found in this zone. Earth bank terraces with a width varying between CT and BT are oriented slightly oblique with respect to the contour, joining in a central access path connecting each platform from uphill-to-downhill. Apart from the terrace morphology, the cultivation related to this practice is comparable to BT, with multiple vine-rows planted in parallel on each platform that is cultivated by the use of machinery.

2.2 | Selection of 50 study sites

In order to ensure comparability of the 50 study sites, an elaborate set of selection criteria were accounted for, with particular attention for reflecting the most representative conditions of this wine production zone.

With regards to soil properties, we utilised the available information from the open-source database by the regional environmental protection agency *Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto* (ARPAV), providing two variables for site selection. In terms of soil texture, we selected 'clay' soils for our analysis, being the most representative soil type of this wine production zone (USDA classification of the upper 100 cm; ARPAV, 2018). Furthermore, in terms of soil permeability the USDA class 'moderate-low' was selected for this study (saturated conductivity between 0.36–3.6 mm hr^{-1}; ARPAV, 2008), as the most common class in this zone and representing a relatively high potential of overland flow. The overlapping spatial extents of these particular soil texture and permeability classes were then extracted using GIS software in order to determine the potential zone of site selection based on soil properties.

With regards to slope steepness, we defined the extent of potential sites by a hillslope inclination ranging from 30 to 45%. Homogeneity of these criteria was explored mostly on remote sensing data available for an entire wine consortium, of which the origins and details are further discussed in Section 2.3. While a common definition of steep-slope agriculture has a minimal inclination of 12% (FAO, 1999), we defined a narrower range of study site selections for two reasons. Firstly, preliminary exploration showed that this particular range ensured that each of the 5 distinct hillslope cultivation types (Figure 2) were represented with at least 10 individual vineyards. In addition, vineyard cultivation on these steeper slopes is among the most vulnerable to hydro-erosive processes, which makes these steep-slope vineyards most relevant to study. The final area of potential study sites was then determined in GIS software by overlaying the zone of selected homogeneous soil conditions with the zone of homogeneous slope conditions and determining their overlapping extent.

The resulting zone of potential sites was imported in Google Earth Pro software (version 7.3.4.8248) for identifying 10 vineyards of each cultivation system, giving a total of 50 sites. The 3D visualisation and exploration options of this software facilitated selecting a homogeneous set of vineyards, while three additional criteria were considered: (a) each site represents grass-covered vineyards typical for this zone; (b) each site has a regular shape (i.e., quasi-rectangular), areal size, and maximum slope length; (c) each site has a concave hillslope sinuosity (i.e., runoff flows inwards, not outwards). Criteria (b) and (c) are considered important for producing comparable simulations of water and sediment fluxes, therefore we applied a precise post-selection check and correction for each site in a GIS environment based on high-resolution topographic data (Section 2.3). The total slope lengths of each site were standardised as roughly 50 m for cross-comparability, done by reducing the upslope segment for the larger sites. Finally, a computed map of flow accumulation was used to adjust the lateral borders of study sites with outflowing segments, in order to focus our analysis on flow processes occurring inside each site.

The result of this three-step site selection procedure was a set of 50 sites representative for the 5 different vineyard types, characterised by homogeneous land cover, soils, geomorphological and geometrical conditions. By selecting the most common conditions for each of these variables, these 50 sites represented the overall wine consortium in the best way possible. Furthermore, the climatic variability of this production zone (covering roughly 35 km^2) is very limited, as shown by the variation of two meteorological stations bordering this zone (*Chiampo* and *San Giovanni Ilarione*, with a standard deviation in annual rainfall of 75 mm over the period of 2008–2019; ARPAV, 2019), particularly compared to the much stronger inter-annual variability of rainfall (standard deviation of 425 mm; ARPAV, 2019). In further preparation of model simulations, spatial data on high-resolution topography and land use were prepared for each site (Sections 2.3 and 2.4) as input for the physical SIMWE model (Section 2.5).

2.3 | Topographic data source

The topography of the study areas was reconstructed in 3D using LiDAR data provided by the Italian *Ministero dell'Ambiente e della Tutela del Territorio e del Mare* (MATTM, 2008). Data collection surveys were carried out using ALTM Gemini and ALTM 3100EA scanners. These systems consist of one or two laser heads operating in the near-infrared (1064 nm) that send light pulses at a frequency ranging from 33 to 400 kHz depending on the flight height. The positional accuracy has a vertical component of roughly 15 cm (MATTM, 2008). The provided 3D point cloud already contained a classification of terrain points, facilitating the subsequent steps of interpolation and gridding in order to obtain a DTM with 1-m horizontal resolution.

2.4 | Land cover digitisation

For each vineyard, the internal distribution of vine-rows, access roads, and grass-covered patches and inter-rows was identified and digitised in QGIS software (version 3.4.4) based on an open-access Google Satellite basemap (source imagery from 3/17/2021 by Maxar Technologies 2021) using the QuickMapServices plugin (version 0.19.26). In the digitisation of the vineyards, the standard width of inter-rows (2 m) and vine-rows (1 m) was maintained in order to adequately capture these elements in the 1-m horizontal grid resolution of the simulations of this study. In the identification of access roads, the following distinction was made between regular inter-rows and more heavily trafficked roads: any access path that is necessarily passed more than one time by tractor for each field operation was considered as an access road. Any remaining patch or inter-row strip not classified as vine-row or access road was then assigned a grassland cover class (including the inclined terrace banks), justified by the omnipresent grass cover throughout vineyard landscapes of this wine consortium.

Various model input values related to the SIMWE model (Section 2.5) were then assigned to these three land cover classes. Firstly, surface roughness values (Manning's *n*) were adopted from a previous study in a vineyard in this zone (Pijl et al., 2020), giving 0.100 for vine-rows, 0.030 for access roads, and 0.035 for grass patches. Infiltration capacity (saturated conductivity) for each class was adopted from the same study based on field measurements, giving 37.3 mm hr^{-1} for vine rows, 3.3 mm hr^{-1} for access roads, and 12.7 mm hr^{-1} for grass patches (Pijl et al., 2020).

2.5 | SIMWE simulations of soil and water movement

The physical SIMulated Water Erosion model (SIMWE; Mitas & Mitasova, 1998) provides spatially distributed simulations of surface processes related to the movement of water and soil particles. Previous SIMWE applications in Mediterranean vineyard conditions yielded satisfactorily and validated results in modelling runoff and erosion processes, ranging from plot scale (Straffelini et al., in prep), to field scale (Pijl et al., 2020), to valley scale (Fernandes et al., 2017). SIMWE consists of two components that can be used separately and are integrated into GRASS GIS software. The first is a hydrological component (r.sim.water; Neteler & Mitasova, 2008), which was used to simulate a 5-min intense rainstorm of 182 mm hr^{-1} for each study site. This intensity was based on the 5-min maximum records averaged from the two local meteorological stations of *San Giovanni Ilarione* and *Chiampo* during the devastating event of 29 August 2020 (ARPAV, 2020). This model component then performed water flow simulations according to a bivariate form of the Saint-Venant equations, relying on spatial input data of topography (Section 2.3), infiltration capacity and surface roughness (Section 2.4). The second SIMWE component simulates sediment detachment, transportation and deposition (r.sim.sediment; Neteler & Mitasova, 2008) based on spatial input data of topography, surface roughness, and simulated overland flow depth provided by r.sim.water. Soil-specific model parameters were based on literature values for 'grassed clay soils' as reported by the model developers (Mitas & Mitasova, 1998), giving a detachment capacity coefficient of 0.0001 s m^{-1}, a transport capacity coefficient of 0.01 s, and critical shear stress of 0.01 Pa. The 50 SIMWE model simulations related to this study were automated by scripting.

2.6 | Zonation and comparison of uphill versus downhill simulations

In order to fully investigate the SWC effectiveness of each of the 5 vineyard practices, we defined a set of diverse indicators based on SIMWE model output, used in further analysis in this study:

- **SDF**: overall sediment flux occurring throughout each vineyard, expressed in g m^{-1} s^{-1}. Higher values thus indicate lower SWC effectiveness, reflecting a measure of general transportation of soil particles across the slope as well as the velocity of this movement.
- **ERS_{uphill}**: erosion rate occurring in the upper segment of any given study site, expressed in g m^{-2} s^{-1}. For the zonation of this indicator (as well as the following two indicators), each vineyard was systematically divided into an uphill and a downhill segment based on elevation (Figure 3). The upper segment consisted of the higher 80% of the elevation model and reflects the actually cultivated hillslope itself, whereas the lower 20% reflects the run-out zone of each vineyard (this division was determined in the preliminary phase of this work by testing and visual validation). Higher ERS_{uphill} thus implies lower SWC effectiveness, indicating soil loss within the actual cultivated area with long-term possible impacts on production.
- **$DPS_{downhill}$**: deposition rate occurring in the lower segment of any given study site, expressed in g m^{-2} s^{-1}. The same zonation approach described above was used for this indicator, but focussing on deposition in the lower 20% of the vineyard (Figure 3). In doing so, internal displacement of soil particles within the cultivated slope is not accounted for, but rather the soil that is actually lost from the hillslope and deposited downhill. Higher $DPS_{downhill}$ thus reflects lower SWC effectiveness, related to the problem of sediment outflux from the cultivated field and downhill sedimentation.
- **$WTD_{downhill}$**: water depth found in the lower segment of any given study site (Figure 3), expressed in mm. We consider downhill water collection as a suitable indicator of the lack of uphill runoff retention

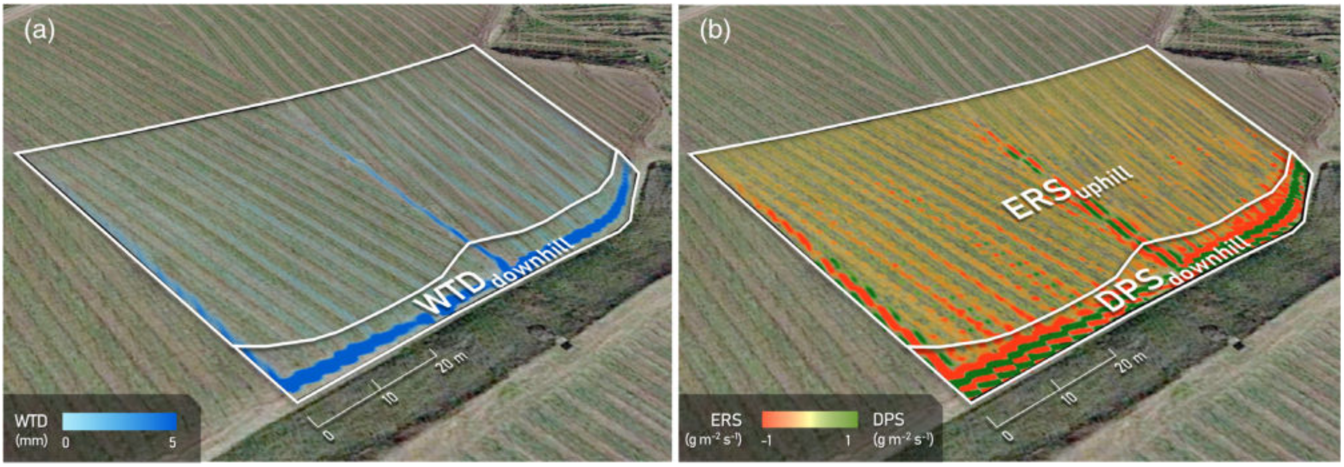

FIGURE 3 Each vineyard was systematically divided into an uphill and downhill segment, respectively corresponding to the upper 80% and lower 20% of elevation values of each site. SIMWE simulations of water depth WTD (a), erosion ERS and deposition DPS (b) were analysed separately in this study, in order to distinguish between impacts within the actual cultivated area and impacts in the runout area downstream (figure based on SIMWE simulations in site SC3) [Colour figure can be viewed at wileyonlinelibrary.com]

(whereas uphill water depth could reflect mixed signals of desirable water storage and undesirable surface flow pathways). Higher $WTD_{downhill}$ thus points to lower SWC effectiveness, related to less water availability for cultivation, potential ponding, or even contribution to downstream flood risk (if occurring on large scales).

In this work, the above indicators were tested for statistically significant differences between the 5 practices. The populations consisted of all grid values belonging to each practice, which were determined and grouped in an R coding environment. For a comparison of practices (Sections 3.1 and 3.2), firstly a one-way ANOVA test was used to determine any differences among the practices, and secondly, a post-hoc Tukey–Kramer test was used to perform pairwise comparisons of each practice. Model accuracy was not analysed in the scope of this study, as the primary focus was on drawing a diagnostic comparison between the 5 practices (and potential simulation bias affected the 50 simulations systematically). Previous research by the authors in the same wine production zone, using the same simulation workflow, has nonetheless highlighted suitable model performance based on qualitative and quantitative validation by field observations (Straffelini et al., in prep; Pijl et al., 2020).

3 | RESULTS

3.1 | Simulated sediment flux in the 50 vineyards

Sediment flux occurring in each of the 50 vineyards under simulated extreme rainfall conditions is shown in Figure 4. Spatial patterns of concentrated movement are visible throughout most sites (in green and yellow colours). The effect of the different vineyard configurations can be clearly recognised in these flow patterns. For instance, slope-wise cultivated vineyards (SC) clearly show parallel flows of sediment through the vine inter-rows (light-blue and green colours in Figure 4), interspersed by lines of low sediment flux related to the vine-rows (dark blue lines). This reflects the even distribution of flow, a common characteristic of the SC practice, although the interrupted slopes lead to increase flow velocity and sediment load in downslope direction (while overall magnitude differences among SC vineyards are also related to differences in slope steepness). In fact, concentrated patterns of sediment flux are commonly found downhill at the roads under the cultivated rows (e.g., visible in sites SC3, SC8 and SC10), or also where vine-rows are planted in a converging pattern (e.g., in sites SC1 and SC3). In the other non-terraced practice (contour cultivation, CC), a similar pattern of high sediment flux values is found downhill (e.g., in sites CC1, CC2 and CC5). However, in CC the vine-rows are planted perpendicular to these flows (dark-blue lines in Figure 4), leading to flow interception and the formation of concentrated patterns across some of the vineyards (e.g., in sites CC7 and CC8) and sideways to the lateral access roads (e.g., in sites CC1, CC8 and CC10).

With regards to the terraced practices CT, BT and OT, a first observation is that large parts of these sites show very limited sediment flux (e.g., semi-transparent and dark-blue colours in Figure 4). These low-flow zones are related to the quasi-horizontal platforms created by terracing (e.g., in sites CT2, CT8, BT5, BT9 and OT8). Nonetheless, high sediment flux patterns are found in these terraced vineyards as well (green and yellow colours in Figure 4), while two recurring situations can be recognised leading to high fluxes, illustrated in Figure 5. Firstly, a concave hillslope sinuosity can lead to strong flow convergence throughout the centre of the vineyard, overtopping the terrace edges in a downslope direction (e.g., visible in sites CT4, CT6, OT4 and OT6). Secondly, access roads are commonly related to flow concentration and high values of sediment flux. Such roads are typically found on the lateral sides of the vineyards along the slope direction and with high steepness (e.g., in sites CT2, BT9,

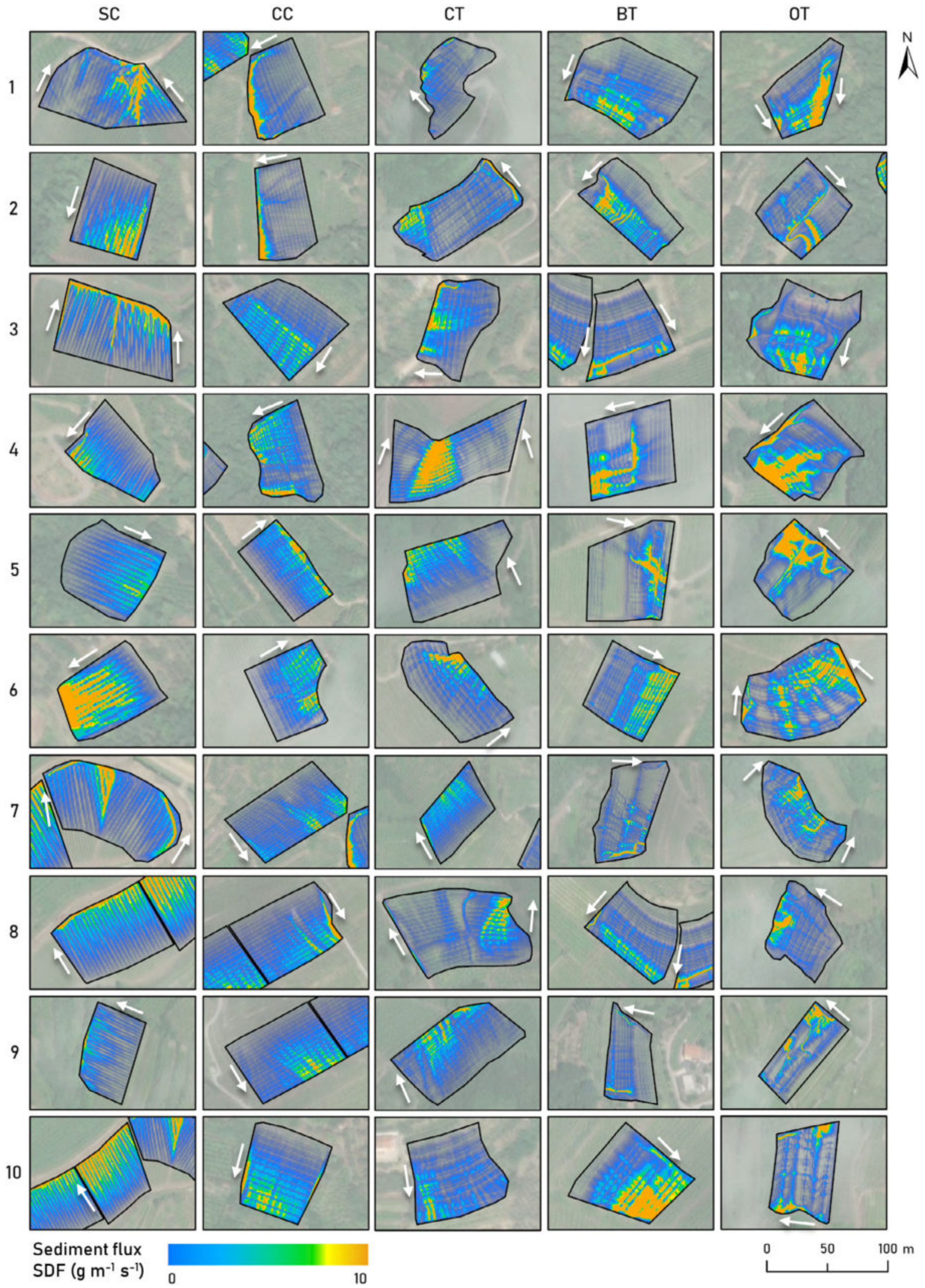

FIGURE 4 Sediment flux SDF (g m^{-1} s^{-1}) simulated using SIMWE for the 50 study sites, comprised of 10 vineyards of the 5 practices slope-wise cultivation (SC), contour cultivation (CC), contour terracing (CT), broad-base terracing (BT), and oblique terracing (OT). Flow patterns are clearly visible running downhill across the vineyards (downslope direction indicated by white arrows), while the impact of vineyard elements are evident, e.g. vine-rows, terraces, or roads [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 Field evidence of common erosive processes directly related to geomorphologic elements of vineyards, highlighted by white arrows. On the left, sheet erosion and a series of shallow landslides were caused by runoff from zigzagging roads. In the centre, an eroded steep lateral access road to a terraced vineyard. On the right, a series of terrace collapses downstream of a hillslope with concave sinuosity. [Photographs by T.A. Vogel (left, right) and E. Quarella (centre)] [Colour figure can be viewed at wileyonlinelibrary.com]

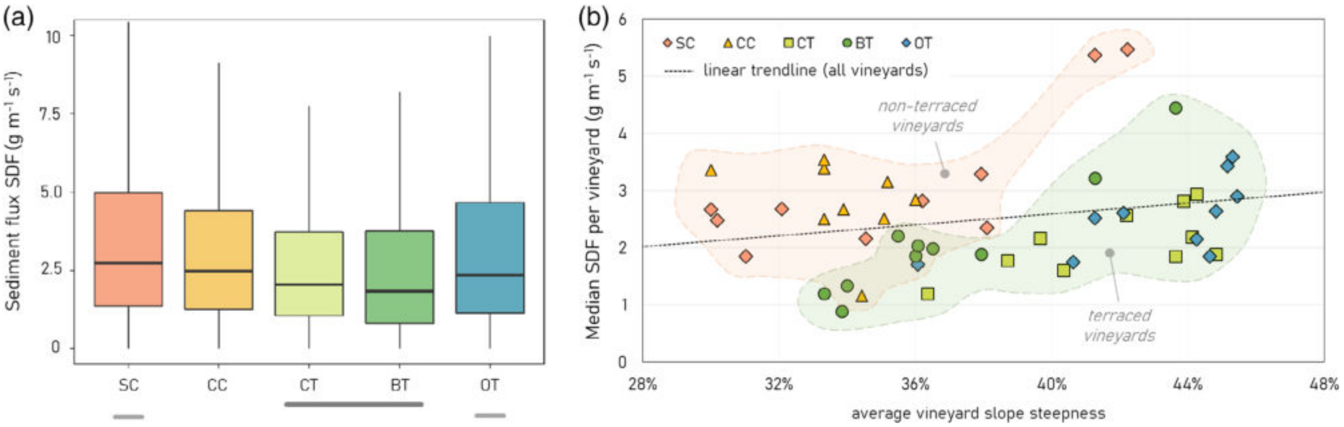

FIGURE 6 Distribution of simulated sediment flux SDF (g m^{-1} s^{-1}) for the 5 practices of slope-wise cultivation (SC), contour cultivation (CC), contour terracing (CT), broad-base terracing (BT), and oblique terracing (OT); with grey bars indicating the practices that were not statistically different according to the Tukey–Kramer test (panel A). Median SDF was also plotted individually for each vineyard against average slope steepness, showing a clear division between non-terraced (SC, CC) and terraced (CT, BT, OT) vineyards in overal SDF-slope relations (panel B) [Colour figure can be viewed at wileyonlinelibrary.com]

BT10 and OT6). Particularly in the oblique terracing (OT) practice, access roads zigzagging throughout the hillslope are responsible for the highest sediment flux of these 10 vineyards, with the roads that connect each platform effectively creating up-to-downhill flow pathways (particularly visible in sites OT2, OT3, OT5 and OT9).

In quantitative terms, the highest sediment flux is related to the group of slope-wise cultivated vineyards (SC; Figure 6a). Across the entire range of quartiles, SC vineyards show the highest degree of sediment movement, with a median value of 2.73 g m^{-1} s^{-1} and a statistical maximum of 10.4 g m^{-1} s^{-1}. The second-highest maximum sediment flux of 10.0 g m^{-1} s^{-1} is found in the oblique terraced vineyards (OT). In fact, the post-hoc Tukey–Kramer test with a 95% confidence interval indicated that no significant differences existed between the SC and OT practices (grey bars in Figure 6a), returning a *p*-value of 0.724. The non-terraced contour cultivated vineyards (CC) finally showed intermediate sediment flux, with a median value of 2.47 g m^{-1} s^{-1} and a maximum of 9.05 g m^{-1} s^{-1}. The lowest sediment fluxes are related to the groups of contour and broad-base terraced vineyards (CT and BT), with no statistical difference found between the two ($p = 0.060$). The median sediment flux found in CT vineyards (2.05 g m^{-1} s^{-1}) is slightly higher than BT vineyards (1.83 g m^{-1} s^{-1}), while the maximum values were slightly lower for CT (7.65 g m^{-1} s^{-1}) compared to BT (8.09 g m^{-1} s^{-1}).

Plotting median SDF values of all 50 vineyards against the average slope steepness provides additional insights (Figure 6b). Firstly, non-terraced vineyards of the SC and CC practice (indicated by the light-orange cloud) generally are more frequently found on gentler slopes (i.e., towards the left), whereas the terraced vineyards of CT, BT and OT (light-green cloud) are found also on steeper slopes (i.e., towards the right). Nonetheless, terraced vineyards are not necessarily showing higher SDF compared to non-terraced vineyards, rather, non-terraced vineyards show similar median SDF on much gentler slopes (i.e., SC and CC vineyards in the slope range of 30–38% have similar SDF values of CT, BT and OT vineyards in the range of 40–45%, Figure 6b). While a linear trendline drawn through all vineyards does not describe a clear relationship (dashed line in Figure 6b, $R^2 = 0.05$), a separate trendline for each practice substantially improved the descriptive value. A group-based linear approximation shows a better fit for slope-wise cultivation SC ($R^2 = 0.62$) and for the terraced practices CT ($R^2 = 0.43$), BT ($R^2 = 0.91$), and OT ($R^2 = 0.40$). Each of these trendlines is showing increasing SDF values with slope steepness, with the most gentle incremental factors for the terraced CT ($A = 0.12$) and OT ($A = 0.14$) and a stronger increase for the non-terraced SC ($A = 0.22$). Interestingly, the BT practice contains among the lowest SDF values of all vineyards (in line with Figure 6a), but these are mostly related to gentler slopes (dark-green points in Figure 6b), while on steeper slopes these vineyards are showing a particularly steep increment of SDF ($A = 0.29$) compared to other practices. This could be understood from the generally tall risers that are required for the construction of broad-base terraces, which are not suitable for steeper slopes.

3.2 | Uphill versus downhill zonation of erosion, deposition and runoff

Analysis of erosion in the upper zone, and deposition or runoff in the lower zone provides more insight into the spatial processes related to each vineyard system. Erosion occurring on the vineyard (ERS_{uphill}, Figure 7a) shows a distribution that roughly resembles SDF (Figure 6a). The most severely eroding are the two non-terraced vineyards (SC and CC, with no significant difference found between them, $p = 0.994$) and oblique terraced vineyards (OT). Contour terraced vineyards (CT) are the least eroding across all quartiles, followed by the broad-base terraced practice (BT). Interestingly, these patterns are somewhat different for the downhill processes. In terms of downhill deposition ($DPS_{downhill}$, Figure 7b), contour terracing (CT) still shows the lowest median, however, statistical testing indicates how many practices are pairwise related according to this variable (indicated by grey bars). In terms of downhill water accumulation ($WTD_{downhill}$, Figure 7c), the CT practice again shows significantly lower values than the other practices. The highest median water depth is related to the non-terraced CC and SC practices (2.04 mm and 1.97 mm, respectively). Nonetheless, both BT and OT practices (with no significant differences between them, $p = 0.999$) show a larger range of values, as well as the highest maximum $WTD_{downhill}$ values of 5.43 mm and 5.11 mm, respectively. In summary, the best SWC effectiveness in terms of all 4 variables is consistently related to practice of contour terraces (CT, Figures 6 and 7). This is contrasted by the non-terraced practices of SC and CC, which typically show the highest soil and water movement as reflected by these 4 variables. Broad-base terraced vineyards (BT) are relatively effective in protecting the hillslope itself due to the large horizontal platforms (Figures 6a and 7a), but still, result in high downhill accumulation of water and soil (Figure 7b,c). This could be related to the steep risers and access roads connecting these platforms, which are similarly responsible for the overall high values of the OT practice (see all maps of simulated erosion, deposition and water depth in Figures A1 and B1).

4 | DISCUSSION

4.1 | Soil and water conservation (SWC) challenges in modern viticulture

The modern-day vineyard landscape in northern Italy consists of a diverse patchwork of different cultivation practices, and a major factor that has been shaping these landscapes is the advent of vineyard mechanisation in the past half-century. While this development boosted vineyard productivity (Corti et al., 2011), several soil and water conservation challenges are arising in these increasingly

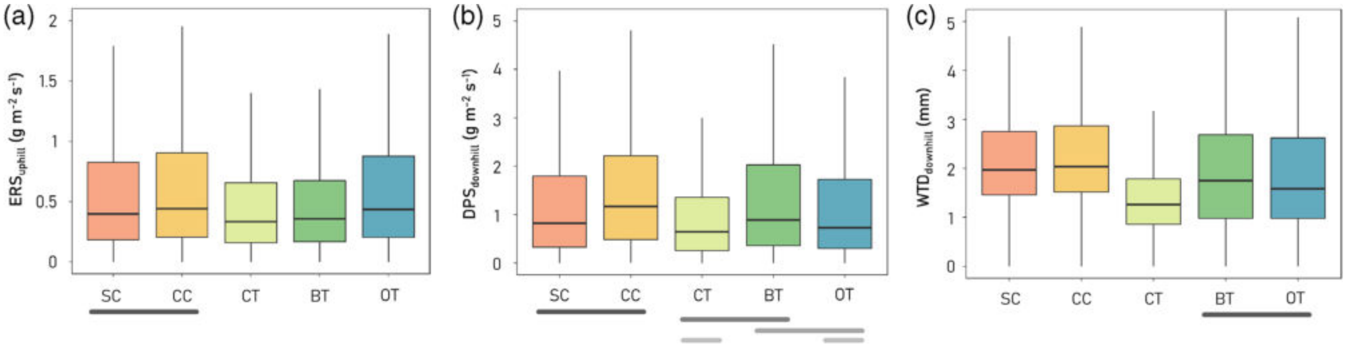

FIGURE 7 Distribution of simulated uphill erosion (ERS_{uphill}, panel A), downhill deposition ($DPS_{downhill}$, panel B), and downhill water depth ($WTD_{downhill}$, panel C) for the 5 practices of slope-wise cultivation (SC), contour cultivation (CC), contour terracing (CT), broad-base terracing (BT), and oblique terracing (OT). Practice pairs that were not statistically different according to Tukey–Kramer tests are underlined by grey bars [Colour figure can be viewed at wileyonlinelibrary.com]

anthropogenic and mechanised landscapes. Firstly, traditional SWC structures such as terraces have increasingly become replaced with monotonous hillslopes (e.g. the SC and CC practices studied here) for facilitated access and higher productive surface (Ramos et al., 2015; Geronta, Ferrario & Turato, 2018). The higher sediment flux, erosion and deposition in non-terraced vineyards reported here indicate the loss of SWC functioning, which is in line with previous studies. Jiménez-Delgado, Martínez-Casasnovas & Ramos (2004) and Ramos et al. (2015) reported increases of around 25% in terms of soil loss after the removal of traditional terracing systems for mechanisation in Spanish vineyards. Field measurements in the same region emphasised how machinery operations such as land levelling and deep ploughing have had substantial impacts on soil profile disturbance, the loss of organic material and soil depth reduction (Martínez-Casasnovas & Ramos, 2009).

Furthermore, the introduction of machinery has implied the need for access roads, which typically represent the steepest and most hydrologically connected parts of the vineyard (Mauri et al, 2021a; Pijl et al., 2019a). Hillslope roads are a widely recognised SWC challenge related to anthropogenic and, particularly, cultivated hillslopes (Preti et al., 2018b; Tarolli et al., 2015), producing high rates of erosion (Pijl et al., 2019a; Sidle & Ziegler, 2012) and potentially contributing to landslide initiation (Galve et al., 2016; Mauri et al., 2021b; Zingaro et al., 2019). Indeed, roads are a recurring factor underlying erosive processes in each of the five practices compared in this study (with evident examples found in SC3, CC2, CT2, BT4 and OT5, showing relatively high values of sediment flux, erosion and runoff). The SWC challenge caused by tractor paths (ranging from high-traffic inter-rows to larger gravel roads) can be attributed to geomorphology as well as soil compaction, as highlighted by Straffelini et al. (in prep) and Pijl et al., (2019a), the latter reporting significantly higher erosion rates on vegetated tracks (+32%) and gravel roads (+67%) compared to non-mechanised vineyards.

These aspects of modern-day vineyard management are thus adversely affecting SWC in vineyards. Considering the five practices compared in this study, the negative impact of mechanisation is most evident in SC, CC, and OT practices, having a strong focus on trafficability (e.g. the uninterrupted parallel inter-row paths in SC and CC, or the centrally connected paths in OT). The results presented here emphasise the need to pursue future-proof designs and management of vineyards, aiming to alleviate rather than aggravate the existing threats of climate change.

4.2 | Indications for future-proof vineyard SWC practices

As elaborated in greater detail by previous studies (Perlotto & D'Agostino, 2018; Pijl et al., 2020; Stanchi et al., 2012) and confirmed by our presented results, the most optimal vineyard configuration balances two functions: (a) intercepting up-to-downstream flow formation by promoting local water storage on the hillslope, while (b) avoiding concentrated flow pathways by evenly distributing surface water across the slope. Vine row orientation plays a crucial role in flow interception, as highlighted in previous research by Bagagiolo et al. (2018), where measured runoff and erosion were found to be >80% lower in contour-oriented rows (CC) than in slope-wise cultivation (SC). In the presented analysis, however, relatively high rates of erosion and deposition in the CC practice indicate that despite its contour orientation, this practice is not optimal for intercepting downslope flow formation under the simulated high-intensity rainstorm conditions. Crucially, the effectiveness of preventing erosive overland flow is dependent on rainfall intensity as highlighted by previous studies. Bagagiolo et al. (2018) monitored >150 erosive events in non-terraced vineyards and showed considerably lower sediment concentration in 'normal' rainfall events (<16 mm hr^{-1}) compared to intense storms. Similar findings were found by Straffelini et al. (in prep) in comparable vineyards, showing a non-linear relationship between runoff or sediment flux and varying rainfall intensities (48–182.4 mm hr^{-1}) that could indicate a threshold value above which accelerated erosion rates occur. Given the increased likelihood of intense rainstorms due to climate change, effective SWC under these conditions is increasingly important. Under the presented high-intensity simulations the contour terracing vineyards (CT) showed an optimal combination of the two aforementioned functions, emphasising the increasing importance of terrace structures under these conditions.

Regardless, even in CT vineyards, a few examples were found of concentrated flows of sediment (Section 3.1) and runoff (Figure B1), indicating that additional mitigation measures are necessary under the conditions simulated here. For instance, sustainable ground cover practices have been shown to significantly reduce runoff and sediment flux (Biddoccu et al., 2016; Galve et al., 2015; Marques et al., 2007), even under intense rainstorm conditions (Straffelini et al., in prep). In addition, while a suitable terracing system is able to absorb sustained precipitation (Arnáez et al., 2015), oversaturation may lead to terrace instability (Camera et al., 2014; Crosta et al., 2003; Preti et al., 2018a) and an improved terrace drainage system may be needed to cope with extreme future meteorological events (Pijl et al., 2019b).

These findings contribute to concrete and robust indications for sustainable and future-proof land and water management in these valuable landscapes. Steep-slope agriculture represents an important source of income, food security, and often cultural landscape value (Wang et al., 2022; FAO, 1999; Tarolli & Straffelini, 2020), highlighting the importance of scientific research about the challenges and opportunities of these landscapes (Tarolli et al., 2021; Tarolli et al., 2014; Wei et al., 2016). As indicated by our results, traditional terracing vineyard systems – when properly designed, maintained and managed – could therefore offer a suitable solution to protecting both the natural resources of soil and water as well as the historical and cultural values of these landscapes.

5 | CONCLUSIONS

We provide an unprecedented in-depth comparison of 5 vineyard configurations of 50 vineyards in terms of several predefined SWC indicators that were systematically and statistically analysed. This approach allowed for robust insights, leading to a concrete evaluation of SWC effectiveness and suitability of the 5 practices under extreme rainstorm conditions, an increasingly common future phenomenon. Overall, regular contour terracing (CT) scored best across all indicators by consistently ranking lowest in terms of sediment flux, uphill erosion, and downhill deposition and water accumulation. In general, the three terraced practices (CT, BT and OT) showed better mitigation of sediment flux than the non-terraced practices (SC and CC), particularly when considering their tendency to be situated on (much) steeper slopes. Nonetheless, the terraced practices of BT and OT still showed relatively high rates of uphill erosion and downhill deposition and water accumulation, which were related to the access paths and taller terrace risers required for creating the broad platforms (as compared to regular terracing). In fact, oblique terracing (OT) ranked similarly poorly in some SWC indicators as the non-terraced SC and CC practices, and indeed all three are designed to favour trafficability.

Given that steep-slope agricultural landscapes are a widespread reality with important economic and cultural values worldwide, a robust evaluation (by the novel methodology presented here) is vital for determining sustainable practices. Future research is encouraged for conducting further comparisons of cultivation systems elsewhere, or for testing their behaviour under diverse climatic conditions. This should go hand-in-hand with further efforts to validate the simulations with field-based observations. Concluding, this work offers at the same time an example for systematic and robust future research, as well as practical insights for the decision-making by land owners, land managers, and land planners responsible for ensuring a sustainable future of these valuable landscapes.

ACKNOWLEDGMENTS

This study was financially supported by the project SOiLUTION SYSTEM “Innovative solutions for soil erosion risk mitigation and a better management of vineyards in hilly and mountain landscapes”, within *Programma di Sviluppo Rurale per il Veneto 2014-2020* (www.soilutionsystem.com) and by the University of Padova research project “ViTE – Vineyard terraced landscapes: understanding the environmental constraints to improve sustainable management” (DALL_FINAC_P14_02). The authors would furthermore like to thank the Italian *Ministero dell'Ambiente e della Tutela del Territorio e del Mare* (MATTM) for providing the high-resolution LiDAR topographic data source underpinning this study.

AUTHOR'S CONTRIBUTION

All the authors wrote, reviewed and edited the manuscript; Anton Pijl, Wendi Wang, Eugenio Straffelini performed the data analysis and produced the figures; Paolo Tarolli conceived, designed and supervised the research.

ENDNOTE

[1] https://blogs.egu.eu/divisions/nh/2020/12/21/climate-change-is-viticulture-under-threat/

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Agnoletti, M., Cargnello, G., Gardin, L., Santoro, A., Bazzoffi, P., Sansone, L., … Belfiore, N. (2011). Traditional landscape and rural development: Comparative study in three terraced areas in northern, central and southern Italy to evaluate the efficacy of GAEC standard 4.4 of cross compliance. *Italian Journal of Agronomy*, *6*(Suppl.1), 121–139. https://doi.org/10.4081/ija.2011.6.s1.e16

Arnáez, J., Lana-Renault, N., Lasanta, T., Ruiz-Flaño, P., & Castroviejo, J. (2015). Effects of farming terraces on hydrological and geomorphological processes. A review. *Catena*, *128*, 122–134. https://doi.org/10.1016/j.catena.2015.01.021

ARPAV (2008). Soil permeability map at 1: 250.000 scale (c0507141_PermSuoliVeneto), provided by the environmental protection agency of the Veneto region of Italy. Metadata: https://geodati.gov.it/resource/id/arpa_ve:c0507141_PermSuoliVeneto. Geoportal accessed on 10 January 2021.

ARPAV (2018). Soil texture map of the upper 100 cm at 1: 250.000 scale (c0507191_TesSuoVen100cm), provided by the environmental protection agency of the Veneto region of Italy. Metadata: https://geodati.gov.it/resource/id/c0507191_TesSuoVen100cm. Geoportal accessed on 10 January 2021.

ARPAV (2019). Monthly summary of meteorological observations obtained for the period of 2008 and 2019 from the environmental protection agency of the Veneto region of Italy at: https://www.arpa.veneto.it/bollettini/storico/.

ARPAV (2020). Meteorological observations measured with a 5-min scale by the environmental protection agency of the Veneto region of Italy, provided upon personal request in the context of this study.

Bagagiolo, G., Biddoccu, M., Rabino, D., & Cavallo, E. (2018). Effects of rows arrangement, soil management, and rainfall characteristics on water and soil losses in Italian sloping vineyards. *Environmental Research*, *166*, 690–704. https://doi.org/10.1016/j.envres.2018.06.048

Biddoccu, M., Ferraris, S., Opsi, F., & Cavallo, E. (2016). Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North-West Italy). *Soil and Tillage Research*, *155*, 176–189. https://doi.org/10.1016/j.still.2015.07.005

Bonardi, L., & Varotto, M. (2016). *Paesaggi terrazzati d'Italia: eredità storiche e nuove prospettive [italian]*. Milano: Franco Angeli.

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., … Panagos, P. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, *8*. https://doi.org/10.1038/s41467-017-02142-7

Brandolini, P., Cevasco, A., Capolongo, D., Pepe, G., Lovergine, F., & Del Monte, M. (2018a). Response of terraced slopes to a very intense rainfall event and relationships with land abandonment: A case-study from Cinque Terre (Italy). *Land Degradation & Development*, *29*(3), 630–642. https://doi.org/10.1002/ldr.2672

Brandolini, P., Pepe, G., Capolongo, D., Cappadonia, C., Cevasco, A., Conoscenti, C., Marsico, A., Vergari, F., & Del Monte, M. (2018b). Hillslope degradation in representative Italian areas: Just soil erosion risk or opportunity for development? *Land Degradation & Development*, *29*(9), 3050–3068. https://doi.org/10.1002/ldr.2999

Camera, C. A. S., Apuani, T., & Masetti, M. (2014). Mechanisms of failure on terraced slopes: The Valtellina case (northern Italy). *Landslides*, *11*(1), 43–54. https://doi.org/10.1007/s10346-012-0371-3

Coppola, E., & Giorgi, F. (2010). An assessment of temperature and precipitation change projections over Italy from recent global and regional climate model simulations. *International Journal of Climatology*, *30*(1), 11–32. https://doi.org/10.1002/joc.1867

Corti, G., Cavallo, E., Cocco, S., Biddoccu, M., Brecciaroli, G., & Agnelli, A. (2011). Evaluation of erosion intensity and some of its consequences in vineyards from two hilly environments under a Mediterranean type of climate, Italy. *Soil erosion issues in agriculture*, eds. D. Godone and S. Stanchi, 113–160. London: IntechOpen.

Crosta, G. B., Negro, P. D., & Frattini, P. (2003). Soil slips and debris flows on terraced slopes. *Natural Hazards and Earth System Sciences*, *3*(1/2), 31–42. https://doi.org/10.5194/nhess-3-31-2003

Cucchiaro, S., Fallu, D. J., Zhang, H., Walsh, K., Van Oost, K., Brown, A. G., & Tarolli, P. (2020). Multiplatform-SfM and TLS data fusion for monitoring agricultural terraces in complex topographic and landcover conditions. *Remote Sensing*, *12*(12), 1946. https://doi.org/10.3390/rs12121946

Diodato, N., Bellocchi, G., Romano, N., & Chirico, G. B. (2011). How the aggressiveness of rainfalls in the Mediterranean lands is enhanced by climate change. *Climatic Change*. *108*(591). https://doi.org/10.1007/s10584-011-0216-4

Eltner, A., Kaiser, A., Castillo, C., Rock, G., Neugirg, F., & Abellán, A. (2016). Image-based surface reconstruction in geomorphometry-merits, limits and developments. *Earth Surface Dynamics*, *4*(2), 359–389. https://doi.org/10.5194/esurf-4-359-2016

FAO (1999). New concepts and approaches to land management in the tropics with emphasis on steeplands. In R. Barber (Ed.), *FAO soils bulletin* (Vol. 75). Rome: Food and Agriculture Organization of the United Nations.

Fernandes, J., Bateira, C., Soares, L., Faria, A., Oliveira, A., Hermenegildo, C., … Gonçalves, J. (2017). SIMWE model application on susceptibility analysis to bank gully erosion in alto Douro wine region agricultural terraces. *Catena*, *153*, 39–49. https://doi.org/10.1016/j.catena.2017.01.034

Galve, J. P., Cevasco, A., Brandolini, P., Piacentini, D., Azañón, J. M., Notti, D., & Soldati, M. (2016). Cost-based analysis of mitigation measures for shallow-landslide risk reduction strategies. *Engineering Geology*, *213*, 142–157. https://doi.org/10.1016/j.enggeo.2016.09.002

Galve, J. P., Cevasco, A., Brandolini, P., & Soldati, M. (2015). Assessment of shallow landslide risk mitigation measures based on land use planning through probabilistic modelling. *Landslides*, *12*(1), 101–114. https://doi.org/10.1007/s10346-014-0478-9

Gao, X., Pal, J. S., & Giorgi, F. (2006). Projected changes in mean and extreme precipitation over the Mediterranean region from a high resolution double nested RCM simulation. *Geophysical Research Letters*, *33*(L03706). https://doi.org/10.1029/2005GL024954

García-Ruiz, J. M., Beguería, S., Nadal-Romero, E., González-Hidalgo, J. C., Lana-Renault, N., & Sanjuán, Y. (2015). A meta-analysis of soil erosion rates across the world. *Geomorphology*, *239*, 160–173. https://doi.org/10.1016/j.geomorph.2015.03.008

Geronta, C., Ferrario, V., & Turato, A. (2018). Preliminary research for conservation purposes of the terraced landscape of Soave, the first Italian historical rural landscape. In A. Bonato & F. Mattiuzzo (Eds.), *Terraced landscapes: choosing the future*, 1(327–337). Venice: Regione Veneto.

Giordan, D., Cignetti, M., Baldo, M., & Godone, D. (2017). Relationship between man-made environment and slope stability: The case of 2014 rainfall events in the terraced landscape of the Liguria region (northwestern Italy). *Geomatics, Natural Hazards and Risk*, *8*(2), 1833–1852. https://doi.org/10.1080/19475705.2017.1391129

IPCC. (2014). *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change* (p. 688). Cambridge: Cambridge University Press.

Jiménez-Delgado, M., Martínez-Casasnovas, J. A., & Ramos, M. C. (2004). Land transformation, land use changes and soil erosion in vineyard areas of NE Spain. In A. Kertész, A. Kovács, M. Csuták, G. Jakab, & B. Madarász (Eds.), *Proceedings volume of the 4th international congress of the ESSC* (pp. 192–195). Geographical Research Institute, Budapest, Hungary.

Marques, M. J., Bienes, R., Jiménez, L., & Pérez-Rodríguez, R. (2007). Effect of vegetal cover on runoff and soil erosion under light intensity events. Rainfall simulation over USLE plot. *Science of the Total Environment*, *378*(1–2), 161–165. https://doi.org/10.1016/j.scitotenv.2007.01.043

Martínez-Casasnovas, J. A., & Ramos, M. C. (2009). Soil alteration due to erosion, ploughing and levelling of vineyards in north East Spain. *Soil Use and Management*, *25*(2), 183–192. https://doi.org/10.1111/j.1475-2743.2009.00215.x

MATTM (2008). Unpublished high-resolution topographic dataset obtained through light detection and ranging (LiDAR) by the Italian Ministero dell'Ambiente e della Tutela del Territorio e del Mare. Made available for the research purpose of this study by personal request.

Mauri, L., Straffelini, E., Cucchiaro, S., & Tarolli, P. (2021a). UAV-SfM 4D mapping of landslides activated in a steep terraced agricultural area. *Journal of Agricultural Engineering*, *52*(1). 1130. https://doi.org/10.4081/jae.2021.1130

Mauri, L., Straffelini, E., & Tarolli, P. (2021b). Multi-temporal modeling of road-induced overland flow alterations in terraced landscape characterized by shallow landslides. *International Soil and Water Conservation Research*. https://doi.org/10.1016/j.iswcr.2021.07.004

Mitas, L., & Mitasova, H. (1998). Distributed soil erosion simulation for effective erosion prevention. *Water Resources Research*, *34*(3), 505–516. https://doi.org/10.1029/97wr03347

Mitasova, H., Barton, M., Ullah, I., Hofierka, J., & Harmon, R. S. (2013). 3.9 GIS-based soil erosion modeling. In J.F. Shroder & M.P. Bishop, *Treatise on geomorphology* (Vol. 3(228–258). San Diego: Academic Press. https://doi.org/10.1016/B978-0-12-374739-6.00052-X

Montanarella, L. (2015). Agricultural policy: Govern our soils. *Nature*, *528*(7580), 21. https://doi.org/10.1038/nature11907

Neteler, M., & Mitasova, H. (2008). *Open source GIS: A GRASS GIS approach*. third edition, Boston, MA: Springer.

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., … Alewell, C. (2015). Rainfall erosivity in Europe. *Science of the Total Environment*, *511*, 801–814. https://doi.org/10.1016/j.scitotenv.2015.01.008

Perlotto, C., & D'Agostino, V. (2018). Performance assessment of bench-terraces through 2-D modelling. *Land Degradation & Development*, *29*(3), 607–616. https://doi.org/10.1002/ldr.2653

Pijl, A., Barneveld, P., Mauri, L., Borsato, E., Grigolato, S., & Tarolli, P. (2019a). Impact of mechanisation on soil loss in terraced vineyard landscapes. *Cuadernos de Investigacion Geografica*, *45*(1), 287. https://doi.org/10.18172/cig.3774

Pijl, A., Quarella, E., Vogel, T. A., D'Agostino, V., & Tarolli, P. (2021). Remote sensing vs. field-based monitoring of agricultural terrace degradation. *International Soil and Water Conservation Research*, *9*, 1–10. https://doi.org/10.1016/j.iswcr.2020.09.001

Pijl, A., Reuter, L. E. H., Quarella, E., Vogel, T. A., & Tarolli, P. (2020). GIS-based soil erosion modelling under various steep-slope vineyard practices. *Catena*, *193*, 104604. https://doi.org/10.1016/j.catena.2020.104604

Pijl, A., Tosoni, M., Roder, G., Sofia, G., & Tarolli, P. (2019b). Design of terrace drainage networks using UAV-based high-resolution topographic data. *Water*, *11*, 814. https://doi.org/10.3390/w11040814

Preti, F., Errico, A., Caruso, M., Dani, A., & Guastini, E. (2018a). Dry-stone wall terrace monitoring and modelling. *Land Degradation & Development*, *29*(6), 1806–1818. https://doi.org/10.1002/ldr.2926

Preti, F., Guastini, E., Penna, D., Dani, A., Cassiani, G., Boaga, J., … Tarolli, P. (2018b). Conceptualization of water flow pathways in agricultural terraced landscapes. *Land Degradation & Development*, *29*(3), 651–662. https://doi.org/10.1002/ldr.2764

Ramos, M. C., Benito, C., & Martinez-Casasnovas, J. A. (2015). Simulating soil conservation measures to control soil and nutrient losses in a small, vineyard dominated, basin. *Agriculture, Ecosystems & Environment*, *213*, 194–208. https://doi.org/10.1016/j.agee.2015.08.004

Ramos, M. C., & Porta, J. (1997). Analysis of design criteria for vineyard terraces in the Mediterranean area of North East Spain. *Soil Technology*, *10*, 155–166. https://doi.org/10.1016/S0933-3630(96)00006-2

Sidle, R. C., & Ziegler, A. D. (2012). The dilemma of mountain roads. *Nature Geoscience*, *5*, 437–438. https://doi.org/10.1038/ngeo1512

Sofia, G., Roder, G., Dalla Fontana, G., & Tarolli, P. (2017). Flood dynamics in urbanised landscapes: 100 years of climate and humans' interaction. *Scientific Reports*, *7*(2016), 40527. https://doi.org/10.1038/srep40527

Stanchi, S., Freppaz, M., Agnelli, A., Reinsch, T., & Zanini, E. (2012). Properties, best management practices and conservation of terraced soils in southern Europe (from Mediterranean areas to the Alps): A review. *Quaternary International*, *265*, 90–100. https://doi.org/10.1016/j.quaint.2011.09.015

Straffelini, E., Pijl, A., Otto, S., Marchesini, E., Pitacco, A., & Tarolli, P. (in prep). A high-resolution physical modelling approach to assess runoff and soil erosion processes in vineyards under different soil managements.

Tarolli, P., Pijl, A., Cucchiaro, S., & Wei, W. (2021). Slope instabilities in steep cultivation systems: Process classification and opportunities from remote sensing. *Land Degradation & Development*, *32*, 1368–1388. https://doi.org/10.1002/ldr.3798

Tarolli, P., Preti, F., & Romano, N. (2014). Terraced landscapes: From an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene*, *6*, 10–25. https://doi.org/10.1016/j.ancene.2014.03.002

Tarolli, P., Sofia, G., Calligaro, S., Prosdocimi, M., Preti, F., & Dalla Fontana, G. (2015). Vineyards in terraced landscapes: New opportunities from LiDAR data. *Land Degradation & Development*, *26*(1), 92–102. https://doi.org/10.1002/ldr.2311

Tarolli, P., & Straffelini, E. (2020). Agriculture in hilly and mountainous landscapes: Threats, monitoring and sustainable management. *Geography and Sustainability*, *1*(1), 70–76. https://doi.org/10.1016/j.geosus.2020.03.003

Wang, W., Pijl, A., & Tarolli, P. (2022). Future climate-zone shifts are threatening steep-slope agriculture. *Nature Food*, https://doi.org/10.1038/s43016-021-00454-y

Wei, W., Chen, D., Wang, L., Daryanto, S., Chen, L., Yu, Y., … Feng, T. (2016). Global synthesis of the classifications, distributions, benefits and issues of terracing. *Earth-Science Reviews*, *159*(18), 388–403. https://doi.org/10.1016/j.earscirev.2016.06.010

Zingaro, M., Refice, A., Giachetta, E., D'Addabbo, A., Lovergine, F., De Pasquale, V., … Capolongo, D. (2019). Sediment mobility and connectivity in a catchment: A new mapping approach. *Science of the Total Environment*, *672*, 763–775. https://doi.org/10.1016/j.scitotenv.2019.03.461

How to cite this article: Pijl, A., Wang, W., Straffelini, E., & Tarolli, P. (2022). Soil and water conservation in terraced and non-terraced cultivations: an extensive comparison of 50 vineyards. *Land Degradation & Development*, *33*(4), 596–610. https://doi.org/10.1002/ldr.4170

APPENDIX A.

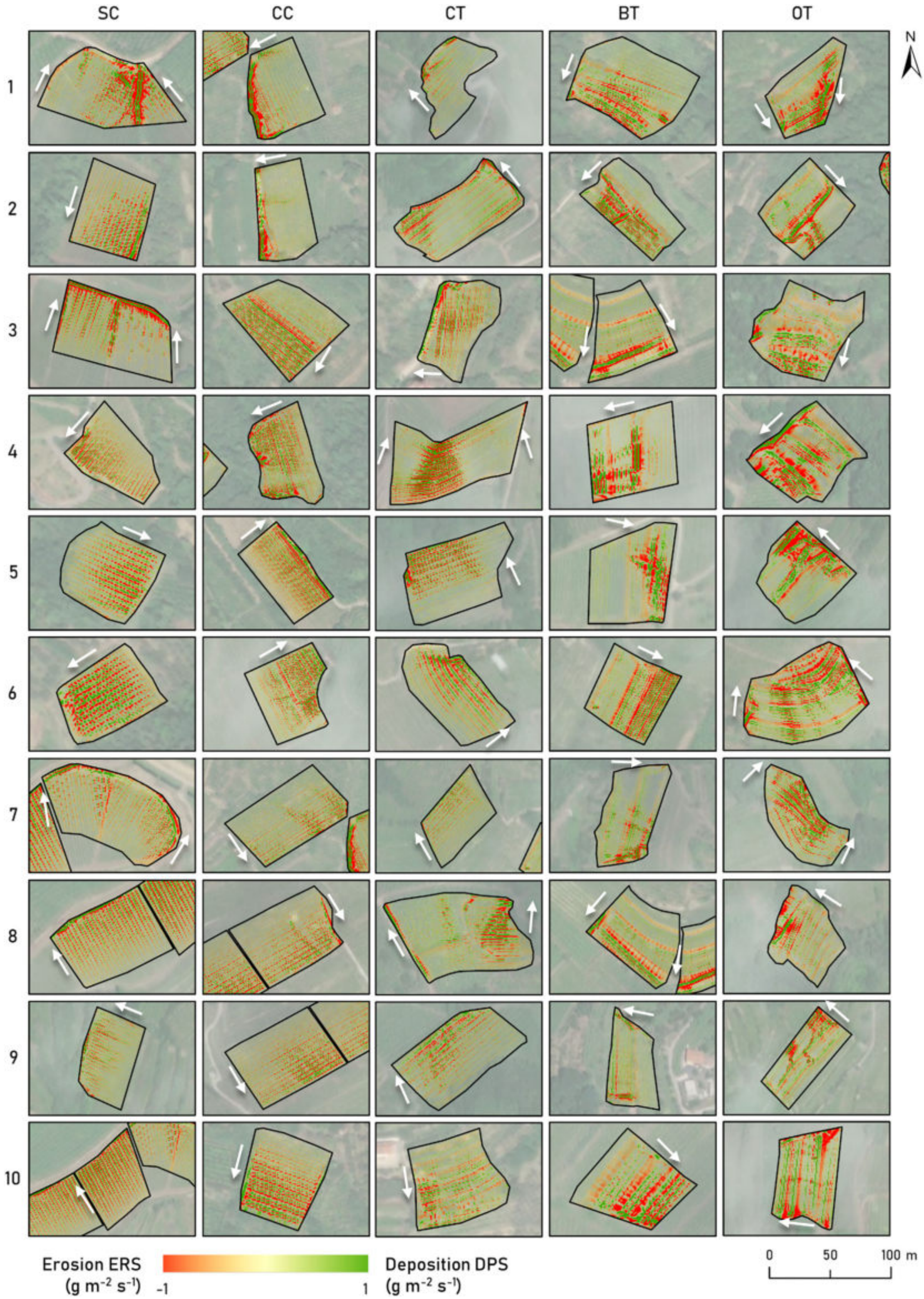

FIGURE A1 Erosion and deposition (g m^{-2} s^{-1}) simulated using SIMWE for the 50 study sites, comprised of 10 vineyards of the 5 practice slope-wise cultivation (SC), contour cultivation (CC), contour terracing (CT), broad-base terracing (BT), and oblique terracing (OT) [Colour figure can be viewed at wileyonlinelibrary.com]

APPENDIX B.

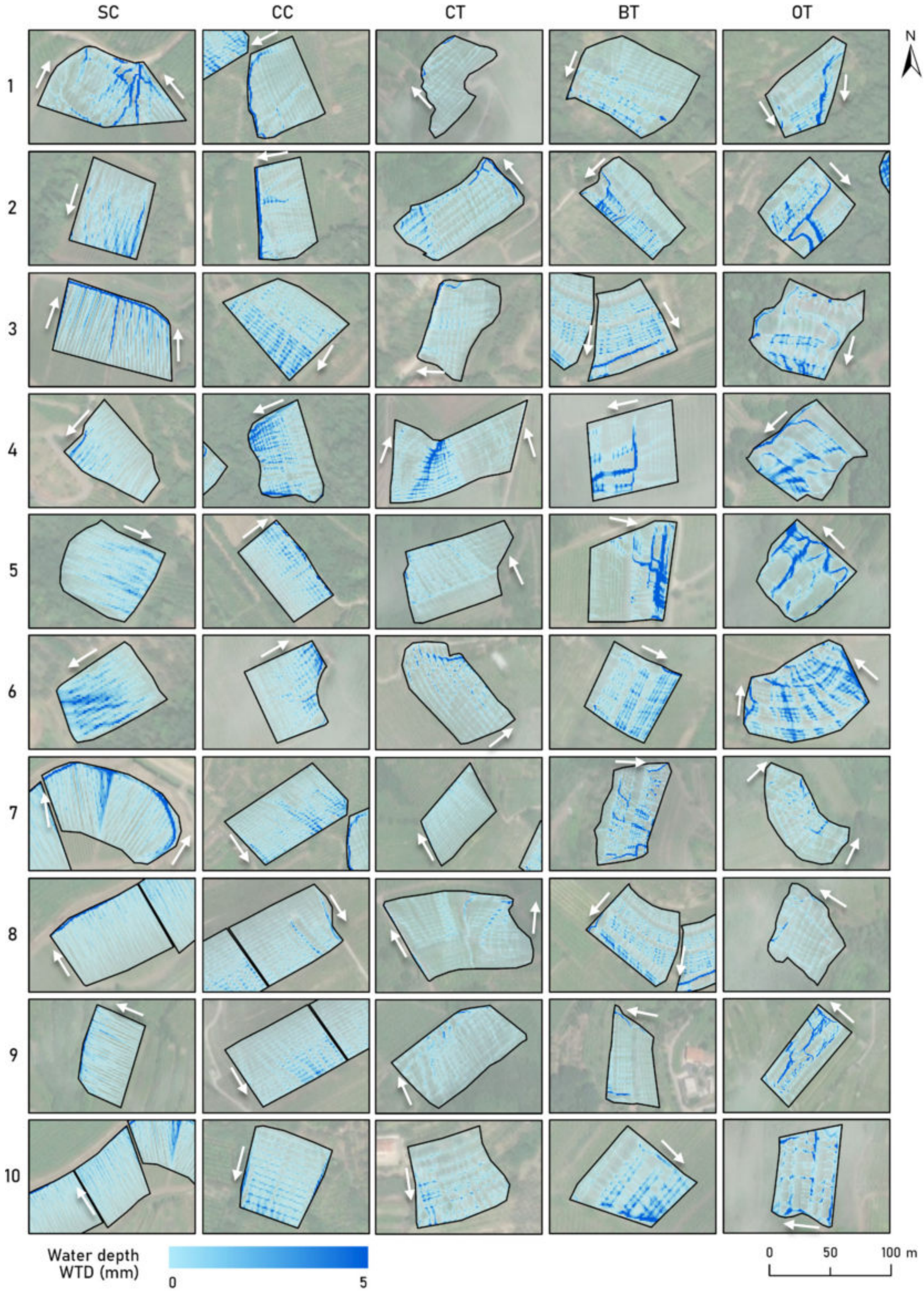

FIGURE B1 Surface water depth (mm) simulated using SIMWE for the 50 study sites, comprised of 10 vineyards of the 5 practice slope-wise cultivation (SC), contour cultivation (CC), contour terracing (CT), broad-base terracing (BT), and oblique terracing (OT) [Colour figure can be viewed at wileyonlinelibrary.com]