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VINEYARDS IN TERRACED LANDSCAPES: NEW OPPORTUNITIES FROM LIDAR DATA

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ABSTRACT

Vineyard landscapes are a relevant part of the European culture, and several authors concluded that they are the agricultural practice that causes the highest soil loss. Grape quality depends on the availability of water, and soil erosion is an important parameter dictating the vineyard sustainability; therefore, soil and water conservation measures are often implemented. Among them, the construction of terraces is the most widely used system. However, while favouring agricultural activities, terraces if not properly maintained can lead to local instabilities creating hazards for settlements and cultivations, and for the related economy. Terraced fields are also served by agricultural roads that can have deep effects on water flows triggering surface erosion. The goal of this research is to use lidar elevation data for a hydro-geomorphological analysis of terraced vineyards. The work is divided in two parts. At first, the Relative Path Impact Index is tested in two vineyards to identify terrace-induced and road-induced erosions. Statistical thresholds of the Relative Path Impact Index are then defined to label the most critical areas. On the second step, using the index and the defined thresholds, we simulate different scenarios of soil conservation measures, establishing the optimal solution to reduce erosion. The results highlight the effectiveness of high-resolution topography in the analysis of surface erosion in terraced vineyards, when the surface water flow is the main factor triggering the instabilities. The proposed analysis can help in scheduling a suitable planning to mitigate the consequences of the anthropogenic alterations induced by the terraces and agricultural roads. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: vineyards; terraces; lidar; high-resolution topography; soil erosion

INTRODUCTION

In Mediterranean and temperate climate regions, vineyards cover mountainous, hilly, coastal and floodplain areas. They represent one of the largest agro-ecosystem (Tonietto & Carbonneau, 2004), and they probably are the most important agricultural activity in terms of environmental impact and income (Raclot *et al*., 2009). One of the most distinctive components of the Mediterranean (Douglas *et al*., 1994, 1996; Gallart *et al*., 1994; Dunjo *et al*., 2003) and semi-arid (Ore & Bruins, 2012) mountain/hilly vineyards are terraces (Tarolli *et al*., 2014). Terraced vineyards witness historic viticulture and agricultural techniques, bearing a high historical and cultural value related to the cultivation of steep sites, and to the craftsmanship of dry-stone walling (Petit *et al*., 2012). Terraced vineyards also possess an inherent aesthetic, social and ecological value, providing diversity of species and biotopes (Höchtl *et al*., 2007).

The purpose of terracing and its effect on hydrological processes depends on geology and soil properties (Grove & Rackham, 2003), but terraces are generally built to retain more soil and water, and to reduce both hydrological connectivity and erosion (Lasanta *et al*., 2001; Cammeraat, 2004). Terraces reduce the slope gradient and length, facilitating the cultivation on steep slopes, and they increase the infiltration of water in areas with a moderate to low soil permeability (van Wesemael *et al*., 1998; Yuan *et al*., 2003), with positive effects on agricultural activities.

Despite their value, terraced vineyards are among the most endangered landscapes in Europe, and they are most commonly threatened by abandonment (Tarolli *et al*., 2014) and subsequent subjection to succession, or else they are transformed to desert vine steppes as part of intensive land consolidation measures (Höchtl *et al*., 2007). As well, in the past, terraced vineyards were planted also in areas that never had hosted vines, including dormant landslides (Corti *et al*., 2011), and hilly soils prone to runoff and erosion (Arnaez *et al*., 2007). As a consequence, they often present erosion and instabilities both on the terraces (Figure 1a and b), and on the nearby structures (Figure 1c).

Literature underlined that there is a relation between the expansion of vineyards and the increase of hydraulic erosion processes (Tropeano, 1984; Costantini, 1992; Kosmas *et al*., 1997; Costantini *et al*., 2001; Pisante *et al*., 2005; Bazzoffi *et al*., 2006; Martínez-Casasnovas *et al*., 2013), with consequences on the loss of nutrients (Novara *et al*., 2013) and in the redistribution of chemicals (Fernández-Calviño *et al*., 2013). Several researches highlighted that vineyards, if compared with other crops, constitute for the Mediterranean areas the form of agricultural land use that causes the

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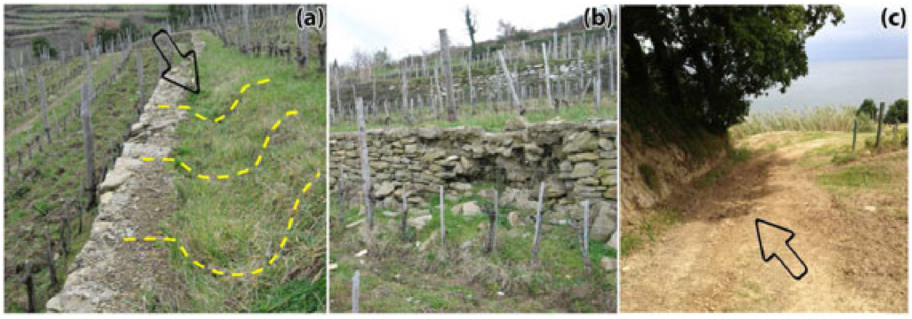

Figure 1. Erosion path covered by grass above a terrace wall (a), and related instability on the terrace (b), and example of erosion area on an agricultural road (c). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

highest soil erosion (Tropeano, 1983; Martínez-Casasnovas & Sánchez-Bosch, 2000; Cerdan *et al.*, 2002, 2006; Martinez-Casasnovas & Ramos, 2006; Cerdà & Doerr, 2007; García-Ruiz *et al.*, 2010). Similar conclusions have been drawn also for other climatological regions (Lieskovský & Kenderessy, 2014).

Terraced vineyards are also served by agricultural roads, and the construction of these anthropogenic features can have deep effects on water flows and instabilities (Tarolli *et al.*, 2013). Roads present in fact a limited soil development (Jimenez *et al.*, 2013), but with high rates of erosion on the roads themselves and on their embankments (Cerdà, 2007), requiring huge investments to reduce the erosion rates (Lee *et al.*, 2013). The plane surface of roads, in fact, can intercept the overland and the subsurface flow (Reid & Dunne, 1984; Luce & Cundy, 1994; Luce & Black, 1999; Borga *et al.*, 2004; Penna *et al.*, 2014) and can modify the natural flow directions expanding the drainage network (Gucinski *et al.*, 2001; Tarolli *et al.*, 2013). The same issues could be induced also by the terrace benches, resulting in local instabilities and/or erosion. As well, the lack of maintenance or an incorrect planning can determine an increase of erosion that can cause the terraces to collapse (Gallart *et al.*, 1994; Lasanta *et al.*, 2001; Crosta *et al.*, 2003; Canuti *et al.*, 2004).

The strict connection between vineyard and terraces management and erosion (Cerdà, 1997; Tarolli *et al.*, 2014) brought the attention to the need of high-quality topographic information. Researchers and land managers, in fact, have called for the development of cost-effective and flexible methods and tools to gather detailed, updated, accessible and specific knowledge of terraced vineyards' characteristic features and of their present state (Tarolli *et al.*, 2014).

Research and Background Motivation

Following this line of research, the aim of this study is to present an application of high-resolution lidar-derived topography for a first and rapid analysis of vineyards terraced landscape. The availability of high-resolution data sets has offered new tools for the mapping of erosion features (Desprats *et al.*, 2013) and the understanding of erosion risk (Leh *et al.*, 2013), and topography from laser scanning technologies provides new and accurate methodologies for land management and planning (Cavalli and Tarolli, 2011; Pirotti *et al.*, 2012; Tarolli, 2014). This study is motivated by the fact that, recently, in many Italian regions, vineyards' terraced landscapes have acquired a special status influencing their management and planning (i.e. the area of Cinque Terre in Liguria, recognized by UNESCO as part of the World Heritage), and practice-oriented guidelines and methods are needed for their correct management.

The proposed work focuses that the erosion in terraced vineyards is mainly connected to the water redistribution (Cammeraat *et al.*, 2010). Erosion is, in fact, facilitated by the changes in the spatial distribution of saturated areas and on the runoff concentration on pathways, and by the insufficient or incorrect drainage of retaining walls (Crosta *et al.*, 2003). Terrace benches are the main sources for generation of runoff contributing to the increase of erosion (Llorens *et al.*, 1992 and Lesschen *et al.*, 2008), and to the increase in earth and water pressures behind the inner face of the retaining wall, main cause of terrace walls collapsing (Tarolli *et al.*, 2014). The most important element to consider to prevent this type of erosion is to analyse properly and regulate overland flows; hence, we proposed to analyse the redistribution of the upslope area because of the presence of terrace benches and agricultural roads. The work considers a methodology previously and effectively applied to different environmental contexts and further explores the use of high-resolution topography and morphological indexes in the analysis and management of terraced vineyards.

MATERIAL AND METHODS

Study Areas

In this work, we consider two terraced vineyards (Figure 2) in Central Italy, where an increasing of surface instabilities was witnessed during the last few years. The two case studies are related to the *Chianti Classico Gallo Nero* vines (*for the Lamole case study, Fattoria Lamole*, Tuscany, Figure 2a, c and d) and to the *Pinot* vines (for the Pesaro case study, *Fattoria Mancini*, Marche, Figure 2b, e and f).

Dry-stone wall terraces are the main feature of the Lamole study. These terraces have a height of about 2 m, while the terraces benches are about 8 to 10 m wide, and they are slightly outward sloped for drainage. Starting in 2003, in

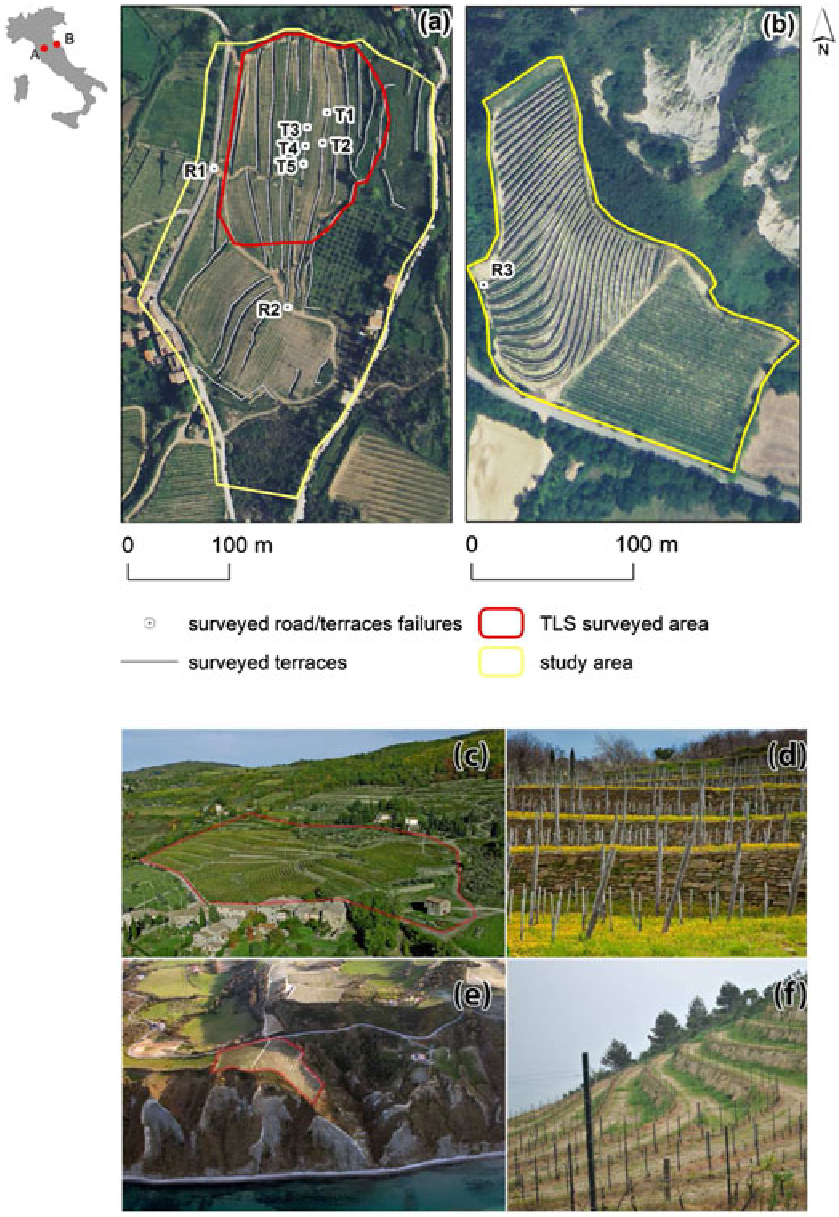

Figure 2. Considered study areas: Lamole case study (a, c and d) and Pesaro case study (b, e and f). Investigated failures surveyed with the DGPS are labelled with T (1 to 5) for terraces failures and R (1 to 3) for road erosion. The small portion of the Lamole area surveyed with TLS is also shown. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Lamole, the restoring of the terraces and the planting of new vines follow an avant-garde project that aims at reaching an optimal level of mechanization as well as maintaining untouched the typical landscape elements.

The Pesaro study area is a small privately owned terraced field. Here, terraces are built with compacted sand, and the terrace risers are generally covered with grass. The terraces generally reach at most 2 m in height, and they present benches about 5 m wide and with a reversed slope.

For both study areas, several field surveys were carried out during spring–summer 2013, and terraced (T1 to T5 in Figure 2) and road (R1 to R3 in Figure 2) instabilities were mapped on the field with differential global positioning system (DGPS).

Lidar Data Sets

Aerial laser scanner digital terrain model

For both case studies, there is the availability of a digital terrain model (DTM) with a 1-m resolution derived from aerial laser scanner (ALS) (Figure 3a and b) (Cazorzi *et al.*, 2013; Sofia *et al.*, 2014a). The DTM has a horizontal accuracy of about ±0·3 m and vertical accuracy of ±0·15 m (root-mean-square error estimated using DGPS ground truth control points) (see the work by Sofia *et al.*, 2014a for a more detailed description of the data set).

Terrestrial laser scanner digital terrain model

In March 2013, using a ‘time-of-fly’’ terrestrial laser scanner (TLS) system Riegl® LMS-Z620 (maximum

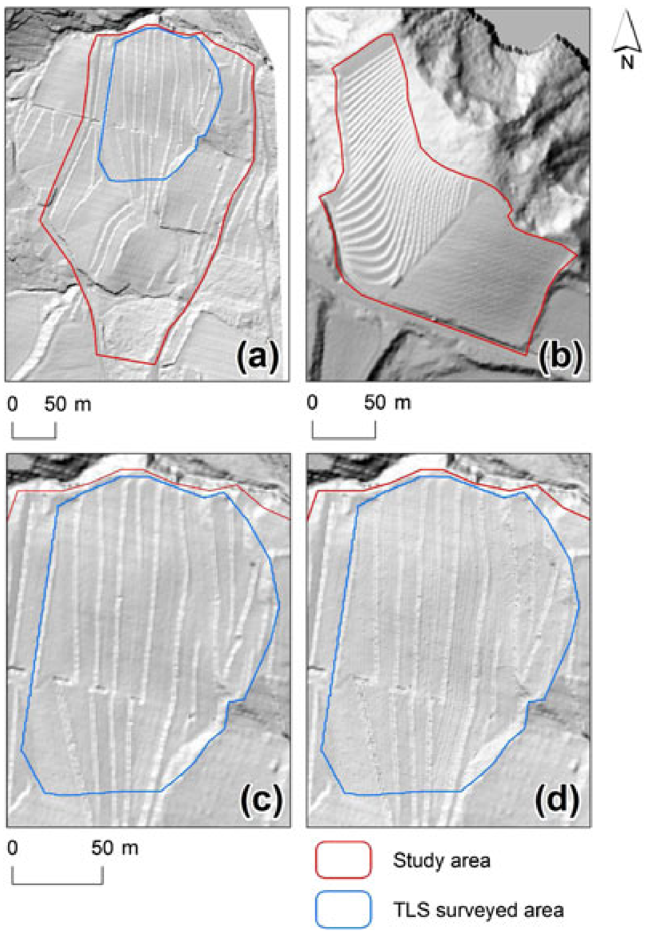

Figure 3. Available ALS DTMs at 1-m resolution for the Lamole (a) and the Pesaro (b) study areas, and comparison between the ALS 1-m DTM (c) and the TLS 0·2-m DTM (d) for the Lamole study area. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

measurement range: 2 km; accuracy: 10 mm; speed of acquisition: up to 11,000 pts/s), we performed a detailed survey of a small portion of the Lamole area, where numerous failures were registered (T1 to T5 in Figure 2). The TLS survey was carried out from six scan positions, in order to have a full coverage of the area of interest. Once acquired, the elevation points were interpolated by the natural neighbour method (Sibson, 1981) to generate a 0·2-m resolution DTM (Figure 3d), with an absolute vertical error smaller than 0·1 m (root-mean-square error estimated using DGPS ground truth control points). This data set provides a more detailed DTM (Figure 3d), if compared with the available 1-m ALS DTM (Figure 3c).

Relative Path Impact Index

To quantify the influence of terraces on the surface flow paths, we applied the Relative Path Impact Index (RPII, Equation 1) proposed by Tarolli *et al.* (2013). This index considers the contributing area as a proxy of the flow path distributions, and in a logarithmic form, it emphasizes and maps areas presenting an increased drainage area because of the presence of anthropogenic features.

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

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

$$Z = ax^2 + by^2 + cxy + dx + ey + f \qquad (2)$$

Where: x, y and Z are local coordinates, and a to f are quadratic coefficients.

In this work, to eliminate the presence of terraces from the smoothed DTM, we applied a 41-m moving window to solve Equation 2. The higher the RPII, the higher the potential runoff-induced erosion is. However, in some case, some RPII high values derive from the smoothing of other morphological forms. As a consequence, the RPII should not be considered an 'absolute' map of erosion but rather as a map that can show the likely sections of a terrace/road subject to potential alteration (Tarolli *et al.*, 2013), and this information can be considered for the identification of possible solutions (see section on Terrestrial Laser Scanner Data and Relative Path Impact Index: A Practical Application), or to provide a location for further and deeper analyses.

Critical values of Relative Path Impact Index

Equation 1 produces maps having widespread RPII values, depending on the amount of differences between the original upslope area and the upslope area derived without terraces. It might be useful, therefore, to identify a threshold discriminant enough for the goal of identifying the most critical areas. A recent literature underlined how statistics drawn from lidar topography carry the signature of some important geomorphic processes (Tarolli & Dalla Fontana, 2009; Sofia *et al.*, 2011; Lin *et al.*, 2013), artificial features (Cazorzi *et al.*, 2013; Sofia *et al.*, 2014a; Sofia *et al.*, 2014b), or errors in the digital maps (Sofia *et al.*, 2013). Starting from this literature, we tested different statistics to identify critical values of the RPII. The considered thresholds are taken from (i) Tarolli *et al.* (2012): multiples of the standard deviation (σ_{RPII}), interquartile range ($\mathrm{IQR}_{\mathrm{RPII}}$) and mean absolute deviation ($\mathrm{MAD}_{\mathrm{RPII}}$); (ii) Lashermes *et al.* (2007) and Passalacqua *et al.* (2010): multiples of the deviation from the normal distribution in the quantile–quantile plot ($\mathrm{Q–Q\ plot}_{\mathrm{RPII}}$); and (iii) Sofia *et al.* (2014a): the bounds defining the outliers in the box plot. See the referenced works for the detailed thresholds definition.

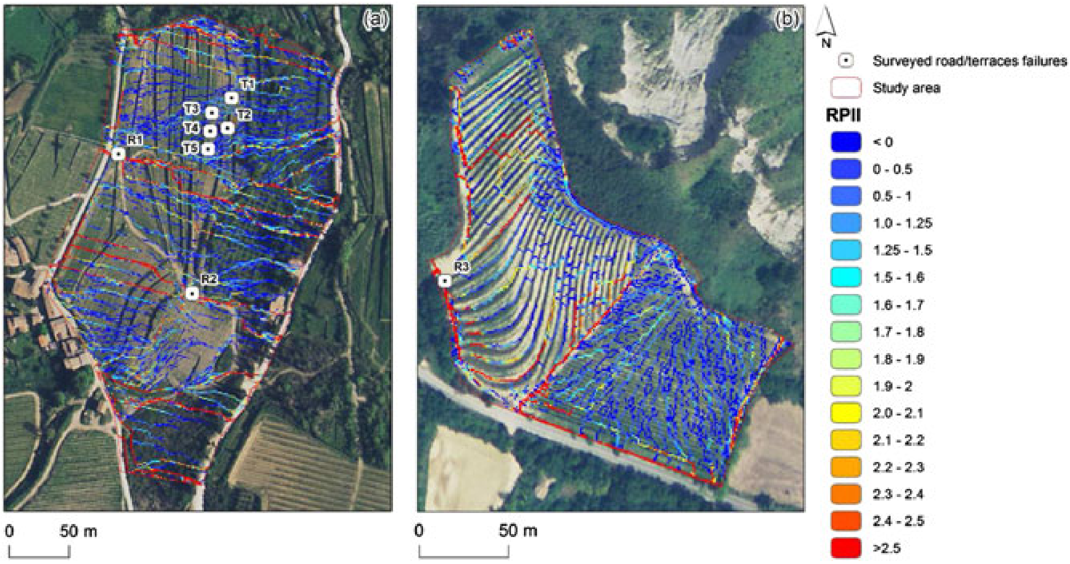

Figure 4. RPII maps derived from the 1-m ALS DTM for the Lamole case study (a) and the Pesaro case study (b), with surveyed terraces instabilities (T1 to T5) and eroded roads (R1 to R3). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

RESULTS AND DISCUSSION

Relative Path Impact Index Analysis

Figure 4 shows the overall RPII map derived from the 1-m ALS DTM of the Lamole case study (a) and the Pesaro case study (b), with the field-surveyed instabilities (T1 to T5 for terraces instabilities and R1 to R3 for road erosion).

As depicted by Figure 4, all the surveyed failures are related to high values of the RPII, underlining indeed how

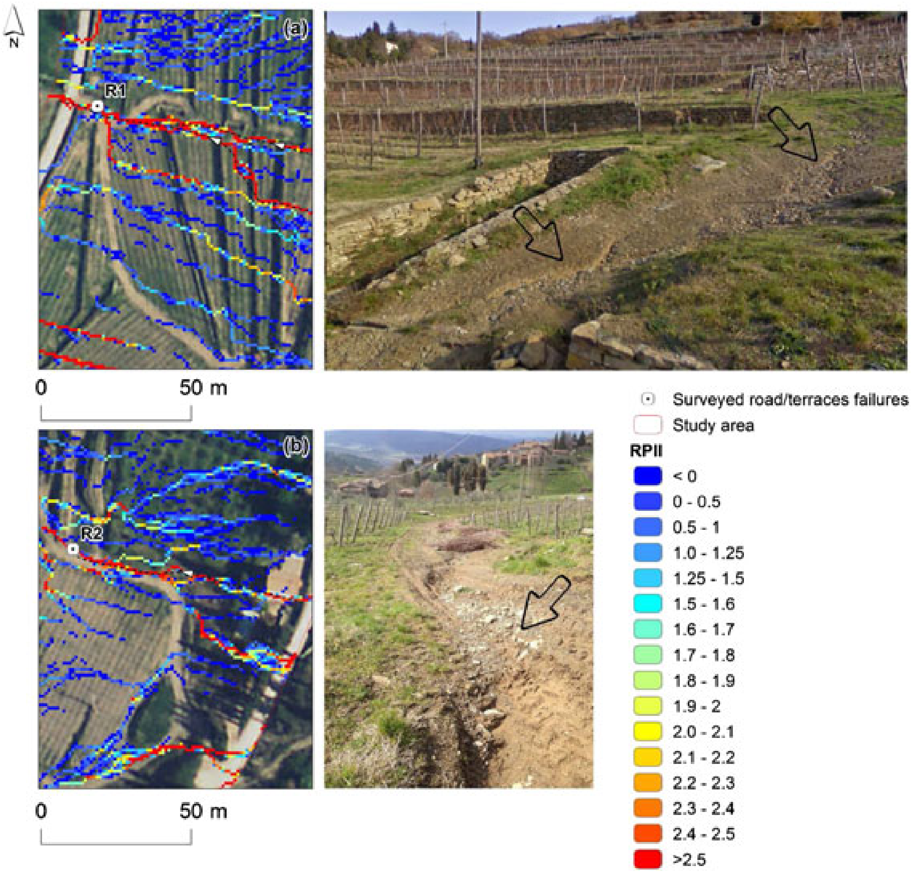

Figure 5. Lamole case study. RPII maps derived from the 1-m ALS DTM, highlighting the flow modifications induced by the road, resulting in road erosion. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

this index is highly effective in identifying the likely sections of areas at risk of collapsing or erosion.

Analysing more in detail the road failures for the Lamole case study (R1 and R2, in Figure 5), the 1-m ALS DTM is able to capture correctly the presence of the road that induces the flow deviation and the consequent flow concentration and erosion on the road itself.

The index here is highly effective because the size of the road (about 2 m in width) is correctly captured using a 1-m DTM. However when considering the terrace failures (T1 to T5 in Figure 6), a 1-m ALS DTM does not seem accurate enough for the correct characterization of the flow alterations causing the problems.

The flow alteration here are probably due to a morphological conformation whose size is best represented when considering as basic topographic information the 0·2-m TLS DTM (Figure 6b): at this resolution, the RPII results more accurate and can depict correctly all the surveyed failures (T1 to T5).

Moving on to the Pesaro case study, using a DTM with a 1-m grid cell size, it is possible to successfully intercept the flow directions' modifications induced by the terraces (Figure 7), which contributed to a deviation of the flows and to an accumulation of water within the agricultural road causing the road disruption.

In both case studies, the methodology could be considered as the first and relatively fast approach to map water surface paths alteration due to roads or terraces presence, as an important factor triggering dry-stone wall instabilities or road erosion. A 1-m ALS DTM is able to capture correctly the terraces and road-induced flow modification determining the erosion surveyed on different agricultural roads. However, to capture the failures on dry-stone wall terraces having a height of 1 to 2 m maximum, a 1-m DTM is not accurate enough, while the availability of a 0·2-m DTM provides the best results.

Critical Values of Relative Path Impact Index

Figure 8 shows the RPII maps thresholded considering one, two and three times the defined threshold (thr). In the figure, the considered thresholds are applied to the RPII derived from the TLS DTM; they are the σ_{RPII} (Figure 8b), IQR_{RPII} (Figure 8c), MAD_{RPII} (Figure 8d), Q–Q $plot_{RPII}$ (Figure 8e) and outliers (Figure 8f).

To test the extent at which the different thresholds can identify terraces/road erosions, we compared values using a Mann–Whitney test, which is a nonparametric test that proposes a null hypothesis where two populations are the same. We deemed the RPII values obtained for the erosion/failures the basic population, and we progressively tested these values against the RPII values larger than multiples of each considered threshold.

From Figure 8, it appears that most of the terraces failures (T1 to T3) are not characterized by outlier values of the RPII (Figure 8f), and the Sofia *et al.* (2014a)

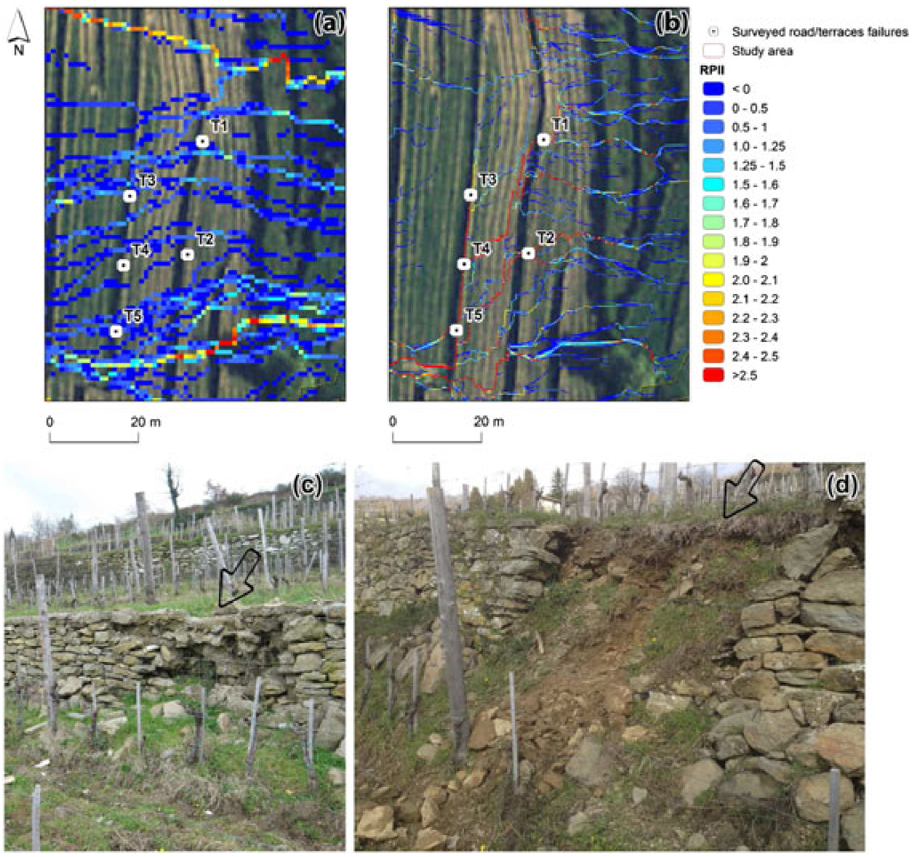

Figure 6. Lamole case study. RPII maps derived from the 1-m ALS DTM (a) and from the 0·2-m TLS (b), highlighting the flow modifications induced by the terraced structures, and the related terraces failures (T1 in (c) and T5 in (d)). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

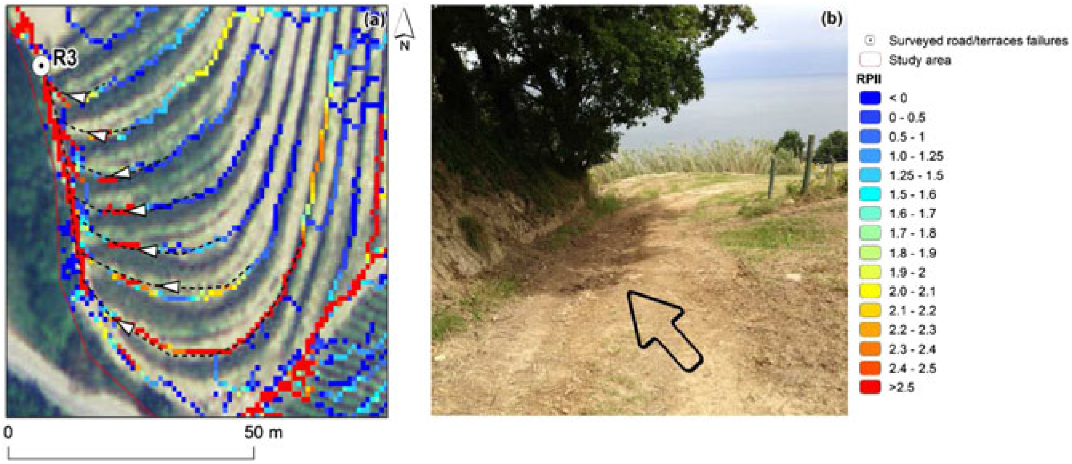

Figure 7. Pesaro case study. RPII maps derived from the 1-m ALS DTM (a) highlighting the flow modifications induced by the terraces, causing water accumulation that erodes the road (b). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

threshold only identifies two out of the five failures (T4 and T5). As well, the results of the Mann–Whitney test confirm the inapplicability of this threshold: RPII values related to the terraces failures are statistically different to RPII values larger than one time the Sofia *et al.* (2014a) threshold (Mann–Whitney test *p*-value 0·0001).

The other statistics (Figure 8c–e) correctly label the potentially critical areas, whereas terraces collapsings seem to be generally related to an RPII higher than one time the value of the considered threshold. Although different statistical thresholds are able to correctly identify the most critical values of the RPII, a threshold value of a multiple of the standard deviation (Tarolli & Dalla Fontana, 2009; Tarolli *et al.*, 2012) (Figures 8b and 9) or of the Q–Q plot_{rpii} (Tarolli *et al.*, 2012) (Figure 8c) results to be more accurate identifying areas potentially at risk of erosion. The results of the Mann–Whitney test for these two thresholds underline a failure of rejection of the null hypothesis at the 5%

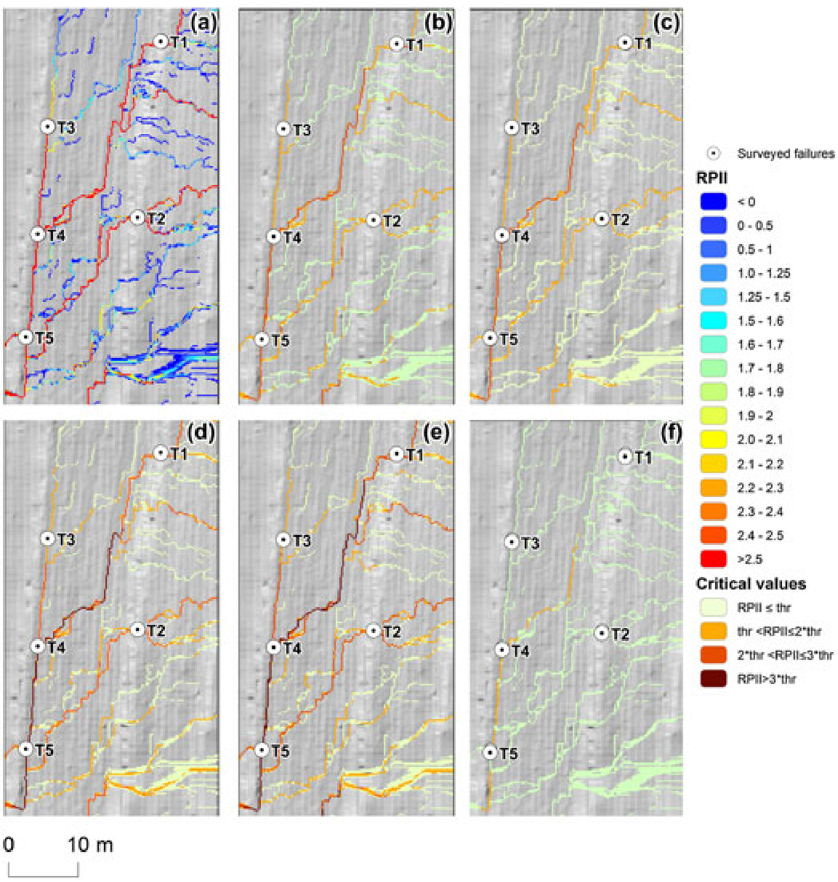

Figure 8. RPII for the TLS surveyed area (a) and extraction of critical values (b–f). The considered thresholds are the σ_{RPII} (b), IQR_{RPII} (c), MAD_{RPII} (d), Q–Q plot_{RPII} (e) and outliers (f). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

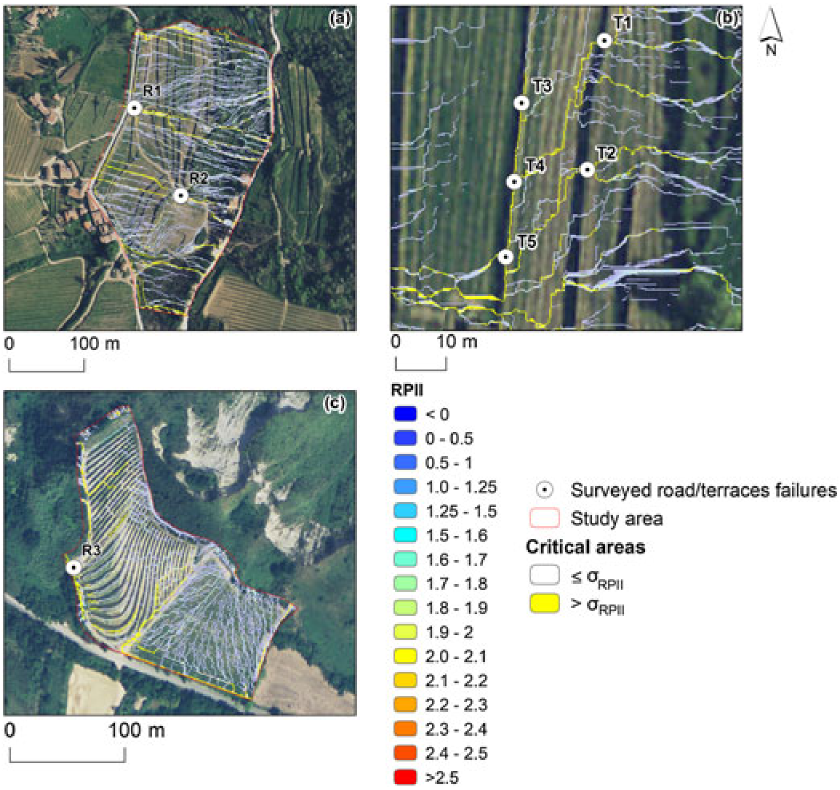

Figure 9. Identification of critical areas (with RPII greater of σ_{RPII}), for the Lamole case study (a and b) and the Pesaro case study (c). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

significance (Mann–Whitney test *p*-value 0·46 and 0·43 for the σ_{RPII} and Q–Q PLOT$_{RPII}$, respectively). This means that the RPII values related to the terraces failures are statistically similar to RPII values larger than one time σ_{RPII} or Q–Q plot$_{rpii}$. As well, from the Mann–Whitney test, it appears that the σ_{RPII} better represents critical areas as a threshold (*p*-value is larger than the *p*-value obtained using the Q–Q plot$_{rpii}$). The results of the Mann–Whitney test for the MAD$_{RPII}$ underlines that this threshold is able to identify values related to the terraces failures, however with a lower power than the σ_{RPII} (Mann–Whitney test *p*-value 0·23).

When we increase the thresholds to multiples of the considered values, the Mann–Whitney test *p*-value indicates in all cases a rejection of the null hypothesis at the 5% significance, meaning that the RPII values measured where the terraces fail are statistically different from the values labelled as critical.

Figure 9 shows the identification of critical areas (with RPII greater than the RPII standard deviation, σ_{RPII}) for the Lamole case study (Figure 9a and b) and for the Pesaro case study (Figure 9c).

As depicted from the Figure 9, considering the σ_{RPII} as threshold, all the areas with the surveyed failures/erosion are correctly labelled.

Terrestrial Laser Scanner Data and Relative Path Impact Index: A Practical Application

When the surface water flow is the main factor triggering the dry-stone wall instabilities, a common soil conservation measure is to reduce erosion by building ditches at the bottom of the terrace risers, to accommodate all runoff created by the terrace itself as well as any tributary runoff that enters the terrace drain. For the Lamole case study, therefore, we simulated on the TLS DTM three different drainage ditch systems (Figure 10), trying to identify the optimal solution to reduce the critical areas (whereas critical areas are identified using σ_{RPII} as threshold). The simulated ditches have a width of 0·2 m (corresponding to the DTM resolution), a depth of 0·2 m and are built to guarantee the hydrological connectivity along the ditch itself.

In the first scenario (Figure 10a), ditches are created at the bottom of the main terrace risers. With this ditch network, the erosion is slightly reduced for the T1 and T2 areas; however, it is not reduced enough (Figure 10d and g). Moving on to scenario 2, the ditch is created in the middle of the bench of the terrace where the T1 and T2 erosions are surveyed. This is a feasible situation, for this peculiar case, because in that position, there is already a change in slope visible on the DTM and that corresponds to a small terrace wall (Figure 10b). By positioning the channel in this location, T1 and T2 do not present anymore high values of the RPII (Figure 10e and h).

Focusing on the terrace failures in T3, T4 and T5, one must note that the scenario 1 and scenario 2 networks do not succeed in reducing the RPII. This is because these failures are caused by an accumulation of water eroding over time the ground on the back side of the dry-stone wall, creating a sort of erosion ditch (Figure 1a). By filling that erosion ditch on the DTM, and adding a drainage ditch at

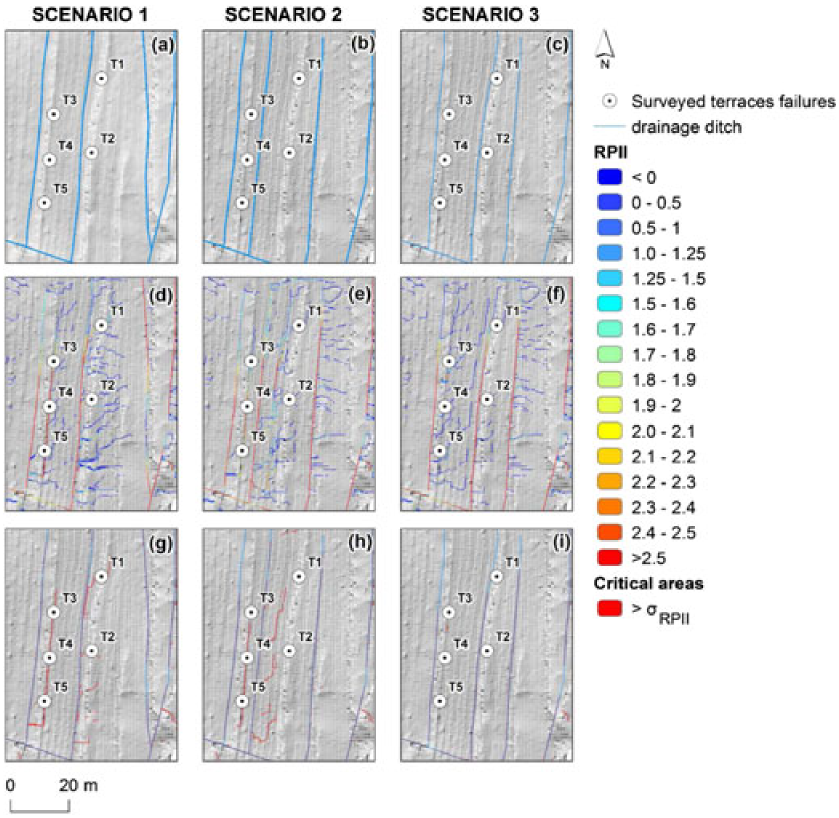

Figure 10. Lamole case study. Simulations of four different drainage ditch systems (a–c) and derived RPII maps (d and e). Figures from (f) to (i) show the critical areas, identified using σ_{RPII} as threshold. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

the bottom of each terrace riser (scenario 3, Figure 10c), the RPII is significantly reduced for all the considered terraces failures (Figure 10f and i).

This example shows how the RPII can be used to help in scheduling correctly the soil conservation measures, to mitigate the consequences of the anthropogenic alterations induced by the terraces structures.

CONCLUSION

This research presented an application of lidar elevation data for a first high-resolution hydro-geomorphological analysis of terraced vineyards. The work is based on the analysis and practical application of the RPII, through the use of high-resolution DTMs and statistical thresholds. The results of this work underlined how the RPII is able to identify correctly terraced failures and road erosions in terraced vineyards, when the surface water flow is the main factor triggering the instabilities. Thanks to this type of support, it is possible to simulate different soil conservation measures scenario, identifying the optimal solution. The proposed approach, therefore, can help in scheduling a suitable planning to mitigate the consequences of the anthropogenic alterations induced by the terraces structures and agricultural roads. One must consider that the construction of dry-stone terraces has been based for centuries on the farmers' empirical knowledge; therefore, spatial databases compatible with modern land-management systems are not always present. Many authorities have nowadays an easy access to qualified and updated high-resolution lidar data, which can be used for the definition of strategies for the conservation of the environment, and to strengthen and improve the quality of the territorial knowledge, and this research underlined how these models can offer easy-to-access tool for land management in terraced landscapes.

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