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ASSESSMENT OF LONG-TERM SOIL EROSION IN A MOUNTAIN VINEYARD, AOSTA VALLEY (NW ITALY)

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ASSESSMENT OF LONG-TERM SOIL EROSION IN A MOUNTAIN VINEYARD

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Assessment of long-term soil erosion in a mountain vineyard, Aosta Valley (NW Italy)

ABSTRACT

In the mountain region of Aosta Valley, NW Italy, grapevine were, in the past, traditionally grown on terraces supported by dry stone walls. Since the 1960s terraces systems were gradually abandoned in favor of an up-and-down the slope row orientation. Tillage and chemical weeding are common soil management techniques adopted in vineyards with high slope gradient, to maintain bare soil. Both techniques expose, to varying degrees, the soil to degradation, favoring runoff and soil losses. Although many studies have focused on effects of soil water erosion in vineyards, there is still a gap in the evaluation of long-term soil erosion rates in vineyards located on very steep slopes (higher than 35%). In order to evaluate long-term soil erosion on a very steep vineyard, a study was carried out on a 44-year old vineyard located at about 900 m asl. The vine rows were oriented up-and-down the slope, which is about 50% (29°). The inter-rows soil management of the vineyard included chemical weeding and, in the first year after plantation, the adoption of irrigation and *hilling-up/taking-out* the soil around the vines. The soil loss was determined adopting the technique of botanical benchmark. According to this methodology the estimated total soil lost over 44 years was about 692 Mg ha^{-1}, with average annual soil loss of 15.7 Mg ha^{-1} year $^{-1}$, confirming that the water and management practices adopted in the vineyard, besides the high slope gradient, have played a relevant role in determining the high erosion rate.

KEYWORDS: soil losses, botanical benchmark, steep slope viticulture, Difference of DEM, GIS.

1. INTRODUCTION

Soil erosion by water is a major agricultural and environmental problem worldwide, since it directly causes fertility decrease, producing nutrient losses and reducing organic carbon stock as well as economic losses (García-Díaz *et al.*, 2016; Ramos *et al.*, 2015; Napoli & Orlandini, 2015; Galati *et al.*, 2015; Lal, 2014; Cerdà *et al.*, 2007, 2009; Cerdan *et al.*, 2010; Maetens *et al.*, 2012; Montgomery, 2007; Martínez-Casasnovas *et al.*, 2005; Morgan, 2009). Furthermore the "off-site impacts" of soil erosion are relevant: water-course pollution from fertilizers and pesticides, supply of sediments into rivers and reservoirs, and muddy floods (Boardman, 2015; Stutter *et al.*, 2012; Gumiere *et al.*, 2011; Boardman, 2010) represent some of the undesirable consequences of the soil erosion process.

As an estimated 12% of Europe's emerged land is subject to water erosion, it has been identified as one of the major threats that affect European agricultural soils, as the European Commission demonstrated by the adoption of the Soil Thematic Strategy in 2006 (CEC, 2006a; CEC, 2006b). In a recent study Borrelli *et al.* (2015) evaluated by means of the RUSLE2015 model, average annual soil losses of 7.43 Mg ha^{-1} $year^{-1}$ in Italy, in the current scenario, which reflects the consequence of the adoption of soil conservation practices (GAEC) as defined in the cross compliance strategy and the European Agricultural Census of 2010.

Grapevine cultivation represents one of the land uses for which higher rates of runoff and sediment losses were observed in Europe, especially in the Mediterranean countries (Kosmas *et al.*, 1997; García-Ruiz, 2010; García-Ruiz *et al.*, 2015; Rodrigo Comino *et al.*, 2016a; Rodrigo Comino *et al.*, 2016b). Analysis of data collected throughout Europe showed that, in the Mediterranean region, runoff rates higher than 9% (Maetens *et al.*, 2012) and the highest erosion rates in Europe (17.4 Mg ha^{-1} $year^{-1}$) are related to vineyard land use (Cerdan *et al.*, 2010).

Under the same land use, factors primarily influencing soil erosion are climate, topography, soil texture, and soil management (Musgrave, 1947; Morgan, 2009; Novara *et al.*, 2013; Lieskovský *et al.*, 2014). Topography, especially slope gradient and slope length, are factors that predispose soil to water erosion (Wischmeier & Smith, 1978; Cerdan *et al.*, 2010; Prosdocimi *et al.*, 2016a). In the past, to make manual cultivation easier and also to intercept surface runoff, management practices such as terracing and rows contouring the slope were generally used in vine cultivation on hill and mountain slopes from Mediterranean areas to the Alps (Stanchi *et al.*, 2012; Corti *et al.*, 2011; Freppaz *et al.*, 2008). This was also the usual system adopted in Aosta Valley as well as in other areas around the Mont Blanc

(Messiez, 1998). Nowadays, small terraces supporting cultivated or abandoned vineyards can be seen throughout the region; these still figure as the main element concerning the most relevant viticultural landscapes in the region (e.g. areas in Donnas, Mont Torrette, Morgex). Well-managed terraces play an important role in slope stability conservation and hydraulic functioning (Stanchi *et al*., 2012). Terraced soils usually have better properties in terms of fertility, organic matter, structure and porosity than the surrounding sloping soils, thanks to rock removal and fertilization (Sandor & Eash, 1995). On the contrary, when terrace management is not efficient, the soil suffers fertility and quality loss, eventually resulting in terrace abandonment and degradation, erosion and soil losses, hydrogeological hazards and slope instability phenomena (Tarolli *et al.*, 2014).

In recent years several studies have been carried out across Europe to evaluate the effect of vineyard soil management on water and soil losses, based on plot or field measurements under natural rainfall during a monitoring period ranging from 2 to more than 10 years (Prosdocimi *et al.*, 2016b). Evaluation of soil losses over a longer time span, up to 250 years, was done by Brenot *et al*. (2008), Casalì *et al.* (2009), Paroissien *et al.* (2010), Novara *et al.* (2011), Vanwalleghem *et al.* (2011), Rodrigo Comino *et al.* (2015) using the benchmark methodology in vineyards ("stock unearthing measurements") and olive orchards.

Most of the studies concerning soil erosion in vineyards were carried out on hillslope areas, with a slope gradient lower than 35% (Prosdocimi *et al.*, 2016b), as this is the typical landscape hosting vineyards. Less attention has been paid to erosion processes in agricultural systems of mountain regions, where the steep slopes and the extreme climate contribute to soil erosion processes, beyond the land use and management (Alewell *et al.*, 2008). In Aosta Valley (NW Italy), viticulture is characterized by vines mainly grown on slopes, which can be very steep or terraced, and by low yield, and high-quality products.

This paper presents a study on a 44-year old steep slope vineyard, located in the Aosta Valley. The methodology based on stock unearthing measurements was adapted and applied, aiming to: (i) quantify the multi-decennial soil erosion in a very steep vineyard; (ii) to identify natural and anthropogenic factors affecting soil erosion in this context.

2. MATERIALS AND METHODS

2.1 The Aosta Valley

The studied vineyard is located in Aosta Valley (Fig. 1), in the western Italian Alps, bordering on France and Switzerland. Most of the regional grapevine production is concentrated in its central part, around the town of Aosta; where the valley is West-East oriented, completely surrounded by high peaks. This area is characterized by unusually low levels of annual mean rainfall: less than 600 mm, with two seasonal peaks in spring and autumn. The mean annual temperature in Aosta (600 m a.s.l.) is about 10°C (Mercalli *et al.*, 2003). Despite the low mean annual precipitation, extreme meteorological events have struck the region over the last decades causing severe floods and landslides, such as those occurred in 1993 and 2000 (AA.VV, 2001; Regione Autonoma Valle d'Aosta, 2010; Luino, 2005). During the period analyzed in the present study, maximum rainfall intensity in Aosta was recorded in 1981: 24.7 mm over 1 hour, 34.8 mm over 3 hours (Mercalli *et al.*, 2003).

In this mountain region, grapevines were traditionally grown on terraces supported by dry stone walls. Since the 1960s, during a period of considerable regional viticulture development, the terraced system was gradually abandoned, while more accessible, larger vineyards planted with rows running up-and-down the slope were generally preferred, on very steep slopes as well (up to 55%). Length of the vine rows reaches 75 m, and exceptionally 100 m. When this layout is adopted on the steeper slopes, the inter-rows cannot be maintained as mown swards, due to passage impracticability and slippage risks for both workers and machinery. In this case, the whole vineyard surface is usually maintained as bare soil, by regular spraying of herbicides. Generally, no particular measure to channel and control surface water is adopted in this area, since it is not usually necessary, due to the low mean annual rainfall.

2.2 The study site

The vineyard named Montcénis (45°45'02'' N, 7°18'50'' E) is located near Aosta. It has been managed by the Institut Agricole Régional since its planting, in 1969 to 2015, when it has been removed. The elevation is about 800 m asl, with southeast orientation and average slope gradient of about 50% (27°). The vineyard covered an area of about 2700 m^2, with rows oriented up-and-down the slope (Fig. 2a); the planting layout was 1.72 m x 0.70 m, and vine density was about 8160 vines ha^{-1}. The length of the rows ranged from 35 to 70 meters. The soil had sandy loam texture, and it is classified as *Dystric Cambisols* (FAO/ISRIC/ISSS, 1998). It is more than 80 cm depth and it has glacial origin. In particular, its origin derives by till deposits characterized by matrix-supported silt-gravel sands with intercalated small cobbles. In 2013, the surface stoniness was about 90% (Fig. 2b) and the skeleton of the top layer of soil (depth 0-10 cm) was about 30%, as reported by soil profiles determined in the vineyard. The sloping area upstream of the vineyard was covered by dense forest since the vineyard plantation until its removal. Its bottom border was retained by a stone wall, which represented the topographic limit downstream of the studied area. The stone wall was interrupted by two stairs leading to the vineyard.

The vineyard was planted with three different grape varieties (Pinot noir, Pinot gris, Müller Thurgau), grafted on Kober 5BB. The management practices adopted in the vineyard varied over time. The soil was kept bare by chemical weeding and, before 2004, rocks were regularly removed from the soil, by hand. In the first 15 years after the vineyard establishment, the technique of hilling-up/taking-out the soil along the rows was adopted, by using a small vineyard plough, to protect the vines from cold weather. Until 2007 the vineyard was irrigated at least once per year by fixed overhead sprinklers; no irrigation was applied from 2008 onwards. All operations in the vineyard were carried out manually by men walking up-and-down the slope, without using tractors, due to the exceedingly steep slope.

2.3 Application of the botanical benchmark technique: determination of the present and original position of the graft union

The soil erosion which occurred during almost the entire vineyard lifespan (1969-2013) was determined adopting the "stock unearthing" technique (Brenot *et al.*, 2008) or "botanical benchmark" technique (Casalí *et al.*, 2009). The technique is based on the assumption that the changes in time of the stock exposure indicate the soil erosion/sedimentation around the vine plant. The grafting callus was used as a marker to identify the soil surface at the planting time.

In the studied area, grafting was carried out mechanically by the nurseryman prior to planting, and did not occur in situ. When planting (Fig. 3a), the graft union must be kept clear from the soil surface in order to avoid root development from the scion (which would make the grafting completely useless). The position relative to the soil of the graft union does not change significantly in the years after plantation. It grows in width, with the formation of the grafting callus, but its height above the soil does not change over time, provided that significant movements of the surrounding soil do not occur (Fig. 3b) (Baldini, 1990 in Casalí *et al.*, 2009; La Marche, 1968).The rootlings were (and still are) planted manually in gravelly soils. When planting, the reference for placing the plant in relation to the soil surface (h_p) was the widest part of the callus, which is easily recognizable. In this study the callus height h_p of the widest part of the callus was measured on the downslope side (Fig. 3c).The current height h_p of the callus from the soil surface was measured for 364 plants, at the same moment as the topographical survey. The sampling density was about one plant every 7.4 m^2. A measurement error of 0.4 cm was assumed for h_p (Eh_p), which was the standard error associated to repeated measurements on a sample of 80 plants.

Based on the direct report of the man who planned and directed the establishment of the vineyard in question, the original height of the graft callus was estimated between 8 cm and 10 cm (a very conservative value) above the soil. This range was confirmed by measurements made on a control vineyard in the surrounding area of the studied plot. According to Casalì *et al.* (2009), the control vineyard must be close and almost contemporary to the studied one, planted using the same methods and its soil surface level must not have changed substantially since the grafting. The vineyard identified as control is adjacent to the studied vineyard, and on similar slope. It belongs to the same wine-farm and was planted in 1998 by the same working staff. Being planted on earth embankments, it is much less prone to erosion, except for an initial loss of soil due to the settlement following the embankment creation (which probably affects the measured callus height as rootlings were planted soon after the earth moving works). Here, the measured mean graft union height was 9.2 cm, with a confidence interval between 8.5 and 9.9 cm (N=80, confidence level=0.95). The value h_o=9.2 cm was thus assumed to represent the height of the graft union at time of plantation. The standard deviation (3.3 cm) represents the spatial variability of h_o and was considered as the human error during plantation (Eh_o), in order to assess the uncertainty of erosion rate estimates.

2.4 Topographical survey

Using a total station Leica TC1010, the entire vineyard surface was surveyed, starting by following a regular grid of 2.10 m (one out of every three plants) x 3.50 m (one out of every two rows). The present coordinates $(x,y,z)_p$ of the base of 364 single plants were recorded, with z_p representing the relative height of the actual soil. The coordinates of points between the rows and along the vineyard's borders were also recorded, in order to assure the best representation of the present soil surface during the construction of the digital elevation model (DEM). Each point sampled (Fig. 4) was representative of an area of about 3 m^2 and the measurement error of the total station is ± 1cm. Finally, the relative coordinates of the points sampled (960 in total) were converted in UTM ED50 coordinates.

2.5 Generation of DEMs of the present and original soil surface

In order to estimate the erosion in the vineyard, two digital elevation models (DEMs) were generated on the basis of the data collected from the topographical survey. The DEMs were obtained with the elevation points interpolation (z_o and z_p). The first DEM depicts the present vineyard surface (DEMp, Fig 5b), based on the actual elevation of soil surface (z_p points). The second DEM represents the estimated topography of the vineyard at time of its plantation (DEMo, Fig 5a), based on the original elevation of soil at the base of each of the sampled plants (z_o), which was calculated as:

$z_o = z_p + \Delta h$ (1)

where:

$\Delta h = h_p – h_o$ (2), with h_o = 9.2 cm.

The resulting original soil surface was located above the present surface if $\Delta h > 0$, whereas the soil surface at the plantation time was below the current height when $\Delta h < 0$.

To individuate the best spatial resolution for DEM creation we made three different analyses: a) evaluation of the density of measured points; b) calculation of the minimum, the maximum and the mean distance between couple of measured points and c) bootstrapping of data. Preliminarily, both the density evaluation and the distances among points were executed using a geostatistical analysis inside GIS and the results were used to find the suitable raster resolution following Hengl’s method (2006). The method individuates the coarsest, the finest and the best (suggested) pixel dimension to use. In this case, we obtained a suggested pixel dimension of 0.4 m and 0.7 m for the DEMp and the DEMo, respectively. Since we have to compare the two rasters, we used the more conservative spatial resolution of 0.7m for both the DEMs.

Secondly, to test the DEMs performance, we carried out bootstrap experiments randomly extrapolating 30% of points from both the DEMo and DEMp with an MSExcel routine. Then, various “sub-sampled” DEMs were created without these points. Each sub-sampled DEM and the whole DEM were compared and the mean standard deviation (0.05 m and 0.07 m for DEMp and DEMo, respectively) was taken to be a preliminary indication of the elevation uncertainty in the interpolation process as in Wheaton *et al*. (2010).

Beside the resolution, the quality of DEM depends also on the interpolation method used for its generation. Furthermore, to create DEMp and DEMo, we tested different methods for interpolation such as kriging, Inverse Distance Weighted (IDW), Triangular Irregular Network (TIN), regularized and tension spline (RST, with various tension and smoothing values). Through a cross validation comparison, the RMSE between measured and interpolated points was our test to evaluate the suitable interpolation approach. Despite its robustness, kriging was excluded because the number of points is few for a correct semivariogram generation. Then, the IDW approach was excluded because it generated simplistic surfaces and the results were less accurate than the other methods. To date, TIN still remains the most computationally practice and widely adopted in literature; however, in our study case, the RST represents the suitable solution considering the number of points and the obtained RMSE values. The RST method computes the values at grid points using a function which simulates a thin flexible plate passing through or close to those points (Neteler & Mitasova, 2008). The tension values determine how the passage through the measured points is closer. This method requires the tuning of the tension parameter to obtain the optimal accuracy of the raster surface: thus, we based again our test on the cross-validation comparison through RMSE between measured and interpolated points, which demonstrated that best results were obtained with the tension parameter t = 55 (RMSE = 0.09 m for both DEMp and DEMo). These RMSE values are comparable with the standard deviation obtained by bootstrapping the data and determine the uncertainty of the interpolation method (see paragraph 4.1).

DEM generation and elaboration has been carried out using open source GIS tools: GRASS (version 6.4.3 – https://grass.osgeo.org/), SAGA (version 2.1.2 - http://www.saga-gis.org/en/index.html) and QGIS (version 2.8.3 – www.qgis.org).

2.6 Estimation of uncertainties in measurements and DEM processing

This paragraph resumes the potential sources of errors of the methodology. Firstly, errors are due to the precision of the measurements of the soil elevation and of the callus height during the field survey. Second, there is no guarantee that the grafting was originally placed exactly at the same height from the ground level for all plants. Furthermore, in the practice of DEM and DEM of Difference the true value is not known and error can only be estimated and formally used as an expression of the uncertainty (Wheaton *et al.*, 2010). Following Brasington *et al.* (2000), the most tangible sources of error in DEM are the precision and the accuracy of the individual surveyed points and the interpolation technique used in surface reconstruction. In this case, errors can derive from: 1) points sampling survey, 2) measurement of callus height 3) interpolation of used algorithms in DEM creation, and 4) propagation of uncertainty in DEM operation. In the latter case, error amplification due to DEM of Difference can be properly included into the classic error theory framework as mentioned first by Brasington *et al.* (2000) and subsequently explained with more details by Lane *et al.* (2003).

2.7 DEM of Difference: construction and raster analysis

Taking into account the quality of surveyed data, the points' density and the small investigated area, we used two different ways to estimate the soil erosion. Preliminarily, we did a simple DEM of Difference (hereinafter GrossDoD) to estimate the gross volume of soil loss (Fig. 5d). As a consequence, the subtraction of the DEM (equation 3) was performed by means of a simple raster calculation, in order to obtain the erosion map:

DEMd = DEMp – DEMo (3)

The new DEMd contains, for each grid, the height (and volume, if multiplied by grid surface) of local soil loss/gain: negative values represent erosion, whereas positive values indicate deposition.

Then, the same equation (3) was used taking in account a uniform propagated error (hereinafter Prop_Err_DoD) following the method exposed in Brasington *et al.* (2000) and Wheaton *et al.* (2010). Thus, presenting the results, we have considered a range of possible amount of long-term soil losses, due to the difficulty of overcoming some of the sources of errors in the application of the methodologies based on botanical evidence (Casalì *et al.*, 2009).

Using GRASS tool r.slope, we additionally derived the slope of the raster surface DEMo (slope_DEM, Fig.5c), in order to investigate a possible relationship between slope and erosion/deposition in the study area. Then, through the utilization of Matlab statistical tools, the nonparametric Spearman correlation test was performed to evaluate the possible significance of the relationship between soil erosion/deposition and slope. The relations between slope_DEM and both GrossDoD and Prop_Err_DoD were investigated, by considering each raster value as a single observation. Afterwards, we made a reclassification of the rasters making both a floating to integer transformation and grouping the data in classes. By grouping the data into 5 cm classes, the reclassification of the GrossDoD generated a new raster surface with 22 classes (DEMd_reclass), in the range -0.40- +0.65. The slope raster reclassification counted 11 classes (slope_DEM_reclass) grouping the slope by 2° between 0° and 36°, with a unique class 0-16° due to the few number of pixels in this range. Then, we combined the two reclassified DEMs in order to count the frequency of each univocal correspondence between slope and erosion. The operation, that is very similar to the logical operation "or", was made with a GIS tool which combines multiple rasters so a unique output value is assigned to each unique combination of input values of the two starting DEMs. The GIS tool assigned the unique output of each couple of data and counts the number of pixel for each unique value. Figure 6a schematizes the elaboration which was carried out, starting from the raster surface slope_DEM and GrossDoD, the subsequent reclassification of both the starting DEMs and, finally the output of the combine operation between the two rasters.

2.8 Effects of vineyard management techniques on soil losses

The effects of the adoption of different management techniques on soil erosion were evaluated by applying the RUSLE model to the studied area, on the basis of the map of soil loss by water erosion in the European Union (Panagos *et al.*, 2015a).

The map was obtained by a modified version of the Revised Universal Soil Loss Equation (RUSLE) model (RUSLE2015, based on Renard *et al.*, 1997) to estimate soil loss in Europe for the reference year 2010:

$$E = R * K * C * LS * P \qquad (4)$$

Where *E*: annual average soil loss (t ha^{-1} yr^{-1}), *R*: rainfall erosivity factor (MJ mm $ha^{-1}h^{-1}yr^{-1}$), *K*: soil erodibility factor (t ha h $ha^{-1}MJ^{-1}mm^{-1}$), *C*: cover-management factor (dimensionless), LS: slope length and slope steepness factor (dimensionless), and *P*: support practices factor (dimensionless).

The raster layers containing estimated soil loss and values for each of the RUSLE factors are available from the European Soil Data Centre (ESDAC) of the Joint Research Centre (http://esdac.jrc.ec.europa.eu/content/soil-erosion-water-rusle2015). The values of different factors and of the estimated soil loss were obtained for the study area from the different maps, whose resolution ranges from 25 m to 1 km (Table 1). The effect of grass cover adoption in the inter-rows (instead of chemical weeding) was considered by changing conveniently the cover management factor (C-factor) and then applying the RUSLE model. According to Panagos *et al.* (2015c) the cover-management factor (C-factor) was slightly lower than the minimum value indicated for vineyards (0.15-0.45). Based on the approach used by Panagos *et al.* (2015c), in non-arable lands the C-factor reaches its minimum value when soil is fully covered by vegetation. On the contrary, in case of a vineyard where chemical weeding is used, the inter-row's soil is maintained bare for long periods during the year. In the studied vineyard, as in many cases in the Aosta Valley, the use of chemical weeding was adopted to assure the accessibility of very steep vineyards with rows oriented up-and-down the slope. Thus, the C-factor value was increased to 0.30, which is a very conservative value for a chemically weeded vineyard.

3. RESULTS AND DISCUSSION

3.1 Estimation of uncertainties in measurements and DEM processing

Errors associated to the datasets creation and processing needed to be considered in the erosion rate estimation. Error associated to z_p was the measurement precision (Ez_p=1 cm). The errors associated to the present and original callus height (Eh_p and Eh_o) were assumed to be 0.4 cm and 3.3 cm, respectively, as above mentioned. Under the assumption of additivity and independence of successive errors, the error associated to the z_o points dataset was estimated using the quadratic sums of the individual errors terms (Paroissien *et al.*, 2010).

$$E\Delta_h = \sqrt{{Eh_p}^2 + {Eh_o}^2} = 3.3\ cm$$

$$Ez_o = \sqrt{{Ez_p}^2 + {E\Delta_h}^2} = 3.5\ cm$$

Thus, the interpolation error associated ($E_{interpol}$) to DEM construction was determined by cross validation through RMSE between measured and interpolated points, as described in the previous paragraph: RMSE = 0.09 m was considered as the interpolation error and the final error resulted respectively:

$$E_{DEM_p} = \sqrt{{Ez_p}^2 + {E_{interpol}}^2} = 9.1\text{cm}$$

$$E_{DEM_o} = \sqrt{{Ez_o}^2 + {E_{interpol}}^2} = 9.7\ \text{cm}$$

Assuming that elevation in each surface contains error that is random, error in individual DEM can be propagated in the Difference of DEM by a quadratic sum (Brasington *et al.*, 2000):

$$E_{DoD} = \sqrt{\left(E_{DEM_p}\right)^2 + \left(E_{DEM_o}\right)^2} = 13.2\ \text{cm}$$

Where $E_{\_DoD}$ is the propagated error in the DEM of Difference and E_{DEMp} and E_{DEMo} are the individual errors in the present and original DEM, respectively. All uncertainties and possible sources of errors are thus considered in the Prop_Err_DoD. As a consequence, the operation considers the highest uniform error which can be committed on the study area.

3.2 Soil loss quantification

The total difference between the present and original DEMs represents the volume of soil loss/gain over the vineyard surface which occurred in the time span from vineyard plantation to its removal (44 years). The mass of soil lost was obtained assuming the bulk density of the soil of 1410 kg m^{-3}, that was estimated from soil samples from the study area. According to this calculation and using (3), the estimated total soil loss obtained from the GrossDoD was about 1370 Mg ha^{-1}, with an annual average soil loss of 31.1 Mg ha^{-1} year^{-1} (Table 2). Taking into account the uncertainties due to the position of the original height of the graft, measurement, interpolation and DEM of Difference operation (Prop_Err_DoD), the final erosion rate was reduced of 50% (15.7 Mg ha^{-1} year $^{-1}$) with respect to the GrossDoD results (Table 2). The estimated erosion rate dramatically exceeds the upper limit of the tolerable soil erosion rates (1.4 Mg ha^{-1} year^{-1}) proposed for Europe by Verheijen et al. (2009). The results obtained at vineyard scale are consistent with erosion rates which were measured in vineyards with similar management, but generally for shorter observation periods and less steep slopes. According to Prosdocimi *et al.* (2016b), the study of Tropeano (1984) referred to the higher steepness (36%) among several measurements collected across Europe. Tropeano (1984) directly measured yearly soil loss of 47.4 Mg ha^{-1} in a tilled vineyard in Piedmont (plot length=25.5 m), over 2 years of observation following its plantation. Novara *et al.* (2011), measured annual erosion of 31.4 and 88.71 Mg ha^{-1} in a Sicilian vineyard, managed with conventional tillage, and located on 16% slope (plot length=140 m).Over a longer time span of 20 years, Brenot *et al.*(2008) obtained an erosion rate of 23 (±9) Mg ha^{-1} year^{-1} for a 133 m long vineyard (and 33 m wide) on 21% slope, by using the botanical benchmark methodology.

Results obtained for the Montecénis vineyard showed that the higher steepness did not correspond to an increase of the average erosion rate with respect to other study cases. However, soil erosion is subjected to high inter-annual variability, due to the variability of rainfall distribution and characteristics (i.e., amount, intensity, energy). A single storm is able to produce very high soil losses in vineyards with bare soil, up to two hundred of Mg ha^{-1}, as was also documented by measurements on less steep slopes (Corti *et al.*, 2011; Ramos & Martínez-Casasnovas, 2004). Furthermore, in the first years after plantation, soil erosion rates are usually expected to be greater, due to soil profile disturbance during the vineyard installation (Ramos & Martínez-Casasnovas, 2007). Casalí *et al.* (2009) observed a decrease in the erosion rates until the vineyards are about 40 years old, then a roughly constant value is reached. In this study case the annual soil losses could also have varied a lot during the 44 years considered, being higher in first years after plantation. We have not evidences of the temporal distribution of soil losses, but we know that some management practices favored the intensity of soil erosion processes, especially in the time when they were applied. For instance, the technique of hilling-up/taking-out the soil along the rows (which resulted in two tillage operations per year), was used in the vineyard for 15 years after plantation and was likely responsible of very intense erosion during this first period of the vineyard lifespan. An evidence of intense soil erosion is the practice of rock fragments removal, which was periodically carried out until 2004. In fact, when the finest particles of soil are detached and transported by the selective water erosion process, coarse elements and rock fragments are left to cover the surface of the soil. The remaining rock fragments are able to protect soil against further water erosion (Blavet *et al.,* 2009). Nevertheless in the studied vineyard rock fragments lying on the surface were periodically removed up and this practice repeatedly exposed the finest portion of soil to erosion.

3.3 Soil erosion spatial variability and soil management effects

Figure 7 shows the erosion maps quantifying the soil losses (negative values) and gain (positive values) over the vineyard surface obtained with equation (3). The erosion maps were obtained considering both the GrossDoD and the Prop_Err_DoD. The latter erosion map, that is represented with black lines delimiting few areas (fig. 7a), takes in account the highest uniform error which can be committed. Thus pixels outside these areas indicate where the height of erosion (or deposition) is uncertain because of the measures, the DEM creation and elaboration. Considering the GrossDoD, the total area of erosion was 2529 m^2 and deposition area only accounted for 123.5 m^2, corresponding to total volume of erosion as 267.7 m^3 and total volume of deposition as 9.6 m^3. Considering the Prop_err_DoD, the total area of erosion decreases to 863.9 m^2 and deposition area only accounted to 26.5 m^2, corresponding to total volume of erosion 137.3 m^3 and total volume of deposition as 6.9 m^3.

In the erosion maps (Fig. 7) wide areas with lowering of soil surface < 13 cm, and thus with uncertain erosion, were observed in a 8-12 meter strip in the upper left portion of the vineyard, with exception of erosion spots at the corners. Thus the assumption that neither runoff nor sediment came from the upstream forest could be considered reasonable. Lower erosion is expected in the top portion of the plot, similar to “the belt of no erosion”, as described by Horton (1945), where erosion occurs at low rate because a minimum slope length is necessary for the development of a rill system (Mutchler *et al.*, 1994). The area including the 7 rows on the left side of the vineyard (observing from the top) shows also erosion substantially lower than 13 cm in first 26 meters. Downstream erosion areas are evident along the rows and along main drainage direction. Areas of relatively intense erosion (locally up to 24 cm of total lowering of the surface) are located between rows 9 and 13 and especially between rows 19 and 21. In both cases erosion was evident along the rows and along main drainage direction, where runoff had a fundamental role in removing soil (blue lines in fig. 7b).

Slight erosion was observed in the bottom and right portion of the vineyard. According to the slope map, the slope angle in the plot was greater than 17°, and mostly over 21°, thus only small deposition areas were observed. During severe rainfall events, runoff and sediments coming from the vineyard were not stopped at the bottom of the parcel, but the runoff and transported sediments flowed out of the plot and then along the road downslope from the vineyard.

Both raster and statistical analysis were performed in order to investigate the relationship between the erosion/deposition obtained by DEMd and the slope of the area. The results of the raster combination (Fig. 6b) reveal that most of erosion (59.1%) occurred on slope between 25° and 29° (between 44% and 51%). The slope class 25°-27° (44%-47%) presented the highest number of cells with erosion (30.2%) and secondarily, erosion was concentrated (29%) on cells whose slope ranged between 27° and 29° (47%-51%). Most cells with slope between 25°-29° were characterized by erosion greater than 10 cm. Less than 2% of cells with steepness lower than 23°(40%) showed erosion, and, surprisingly, it was the same also for slope classes higher than 29° (51%). This analysis did not point out a clear relationship between slope of the each cell and erosion/deposition calculated by the GrossDoD. Also the nonparametric Spearman test revealed no rank correlation between erosion/deposition and slope gradient. Absence of correlation between erosion and slope was also observed in vineyards with mean slope lower than 8° by Casalí *et al.* (2009), who supposed that erosion by water was not the major process responsible of soil losses, which were ascribable to the effect of tillage or mechanical erosion. Similarly, in the Montcénis vineyard, the practice of hilling-up/taking-out the soil along the rows contributed to trigger soil displacement when adopted, resulting in an effect similar to tillage erosion.

The most evident erosion occurred along the main slope direction. The present surface showed a concave shape of transversal section of the inter-rows. In some cases evidence of rills was observed between the vine rows at the time of the surveys, indicating the prevalent role of water erosion. They were generated by rainfall events which occurred in more recent years, when the irrigation system was no longer active and any kind of soil or rock fragments displacement was done. However, soil erosion cannot be entirely ascribed to natural rainfall events. In fact, the irrigation practices, spillage or failures in the irrigation system, probably contributed to the soil erosion by water. Furthermore, in the present study case, high steepness and mountain climate could also have played fundamental role in favoring soil displacement triggered by human trampling and winter erosion, which can be the prevalent soil erosion processes in this kind of environment. Konz *et al.* (2010) identified two dominant erosion processes in alpine environment (slope ranging from 35° to 39°): sheet erosion processes and soil conglomerate movement triggered by animal trampling and followed by gravity forcing. The former process resulted responsible for the mobilization of only the 5-10% of the soil collected in their experiment. Furthermore, erosion rates measured during the growing season were negligible (~1%) compared to those due to winter processes, like snow gliding and melting. In the Montcénis vineyard, a significant rate of the displacement of soil (and rock fragments) was likely due to trampling erosion, given that all operations in the vineyard were conducted by men walking up and down along the steep inter-rows. Finally, a lowering of the soil surface was also evident transversally, along walking paths. In this case it could be due to compaction and soil displacement resulting from repeated passage of men along the same path. The benchmark method allows to assess the total erosion and deposition and net soil losses, and to analyze their spatial variability in the plot. However the methodology does not distinguish the contribution of different erosion processes.

The map showing the soil loss by water erosion in the European Union (Panagos *et al.*, 2015a) gives an annual average soil loss between 18 and 23 t ha^{-1} year^{-1} for the area under observation. The erosion rate that was obtained in this study is slightly lower and higher than that range, considering the Prop_Err_DoD and GrossDoD, respectively. As discussed above, it takes the combined effect of the management practices adopted in the vineyard into account. Moreover, the maintenance of bare soil in the vineyard worsened the effect of water erosion, as was also demonstrated by many studies on less sloping vineyards (Biddoccu *et al.*, 2016; Novara *et al.*, 2011, Ruiz-Colmenero *et al.*, 2011). In fact, considering chemical weeding, by increasing the C-factor value to 0.30, an average soil loss ranging from 40 to 50 t ha^{-1} year^{-1} was obtained by RUSLE. This value can be considered a more appropriate result of RUSLE application to the vineyard than the one obtained with the lowest C-factor, and it is even greater than the average soil loss obtained by the benchmark method (both considering the Prop_Err_DoD and the GrossDoD). The comparison of the results of the benchmark method with the RUSLE model output, suggests that the application of the benchmark method to obtain indication of long-term soil loss gave underestimated values, due to the uncertainties of methodology and if the contribution of additional erosion processes is taken into account. However, since direct measurements are not available in literature and sporadic for such steep vineyards and for long observation periods, the benchmark method could be applied to obtain an indication of the overall impact of the different soil erosion processes and of the spatial distribution of erosion/deposition. To obtain a more reliable evaluation of soil losses and erosion rates, the methodology needs to be improved, reducing as possible uncertainties in its application.

CONCLUSIONS

Despite the uncertainties in the quantification of soil loss, related to the benchmark method, the long-term erosion rate estimated by the study was consistent with values reported for vineyards by other studies, taking into account the different reference time span. The benchmark methodology allows to evaluate the overall impact of different erosion processes, not only erosion by water, playing an important role in determining soil losses in such extreme environment. Nevertheless the methodology needs to be improved, especially if used in very steep and old vineyard, to reduce uncertainties in its application. This study confirmed the relevance of soil erosion in vineyards, particularly where the high slope steepness and other management solutions connected to this feature had a fundamental role in increasing the soil erosion. Such a high soil loss causes a significant degradation of this resource in a few years. Soil erosion by water was emphasized by the mountain environment (very steep slopes and climate) and by management solutions adopted in the vineyard (orientation of the rows up-and-down the slope, regular application of chemical weeding, men trampling up-and-down the vineyard, tillage), which resulted in additional soil erosion. Some management solutions could be adopted in the region, to limit the impact of soil erosion. The conservation of old terraces and the creation of new ones, as well as the adoption of earth embankments should be encouraged to reduce soil losses, allowing also some mechanization and grass cover in the vineyard, and less tiring work for men.

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Table 1- Value of the each RUSLE factor which was assigned to the studied area in according to the RUSLE 2015 methodology, and value of the modified factor.

RUSLE factor	Dimension	Value	Source/description
RUSLE 2015			
R-factor	MJ mm ha^{-1} h^{-1} yr^{-1}	675-707	Panagos et al., 2015b
K-factor	t ha h ha^{-1} MJ^{-1} mm^{-1}	0.02	Panagos et al., 2014
C-factor	-	0.14	Panagos et al., 2015c
LS-factor	-	10.52-10.63	Panagos et al., 2015d
P-factor	-	1	Panagos et al., 2015e
Chemical weeding			
C-factor	-	0.3	Panagos et al., 2015c Mean value of C-factor for vineyard

Table 2 – Total volume of soil loss obtained from the total difference between DEMs, as simple DoD (GrossDoD) and considering the uniform error (Prop_Err_DoD). Total soil loss and average annual soil loss were obtained considering soil bulk density of 1410 kg m^{-3}.

Type of analysis	Volume of erosion (m^3)	Volume of deposition (m^3)	Total soil loss (m^3)	Total soil loss (t ha^{-1})	Average soil loss (t ha^{-1} $year^{-1}$)
GrossDoD	267.7	9.6	-258.1	1370	31.1
Prop_Err_DoD	137.3	6.9	-130.4	692	15.7

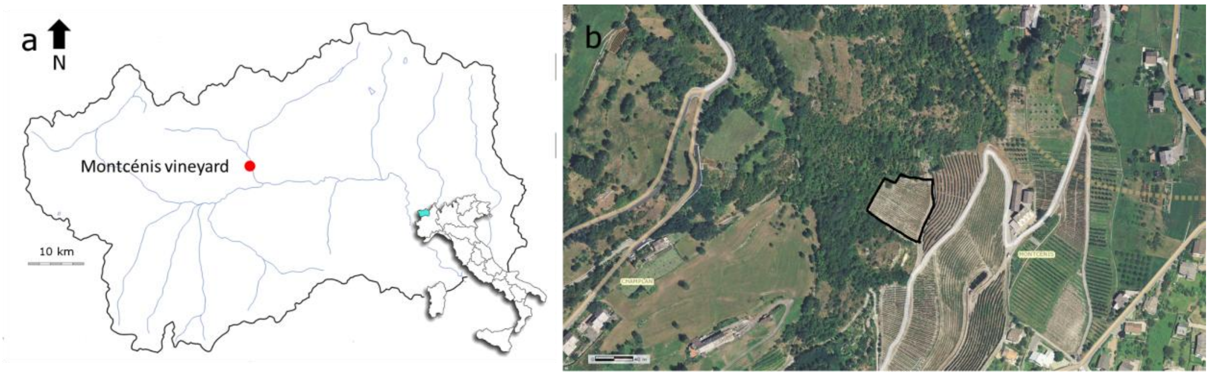


Figure 1 - Location (a) and aerial view (b) of the studied vineyard in Aosta Valley, NW Italy.

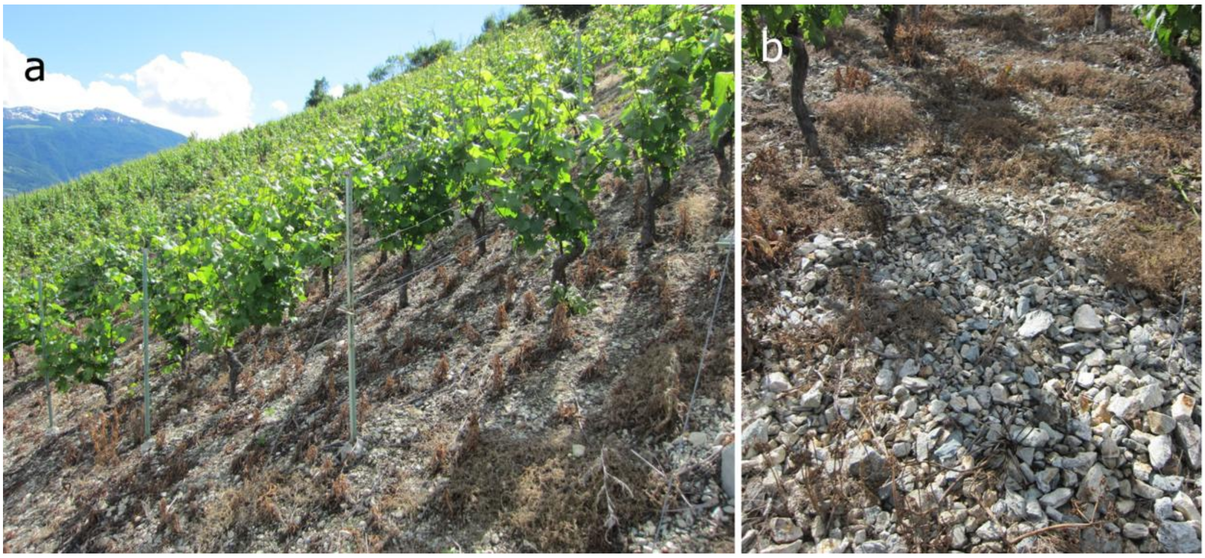


Figure 2 – View of the studied vineyard from the bottom, with rows aligned up-and-down the slope (a) and of the present soil surface, with high percentage stoniness (b).

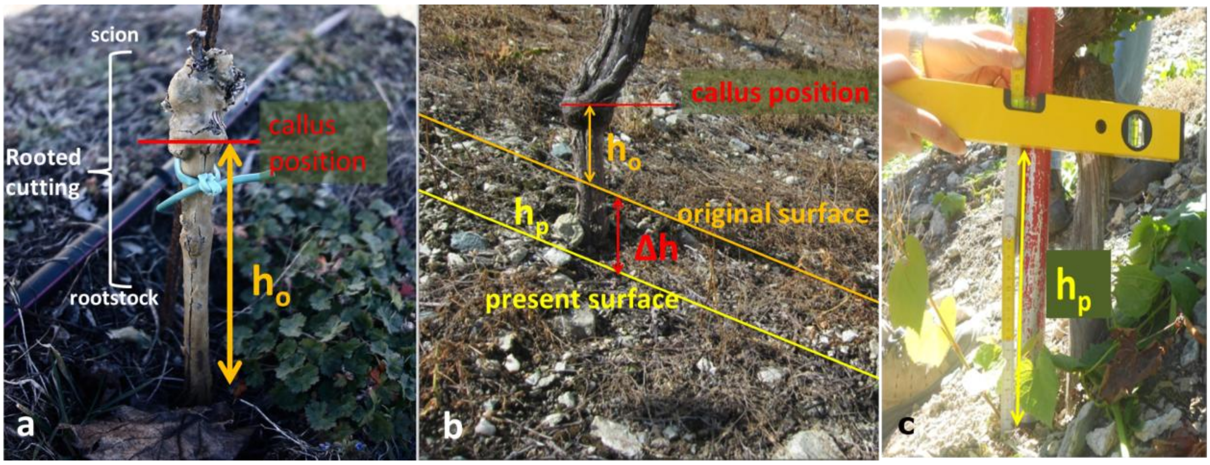


Figure 3 - The position of the callus in a (a) just planted (ho) and (b) old (hp) vine plant, with schematic representation of present and original soil surface, and (c) measurement of the current height hp of the grafting callus from the soil surface.

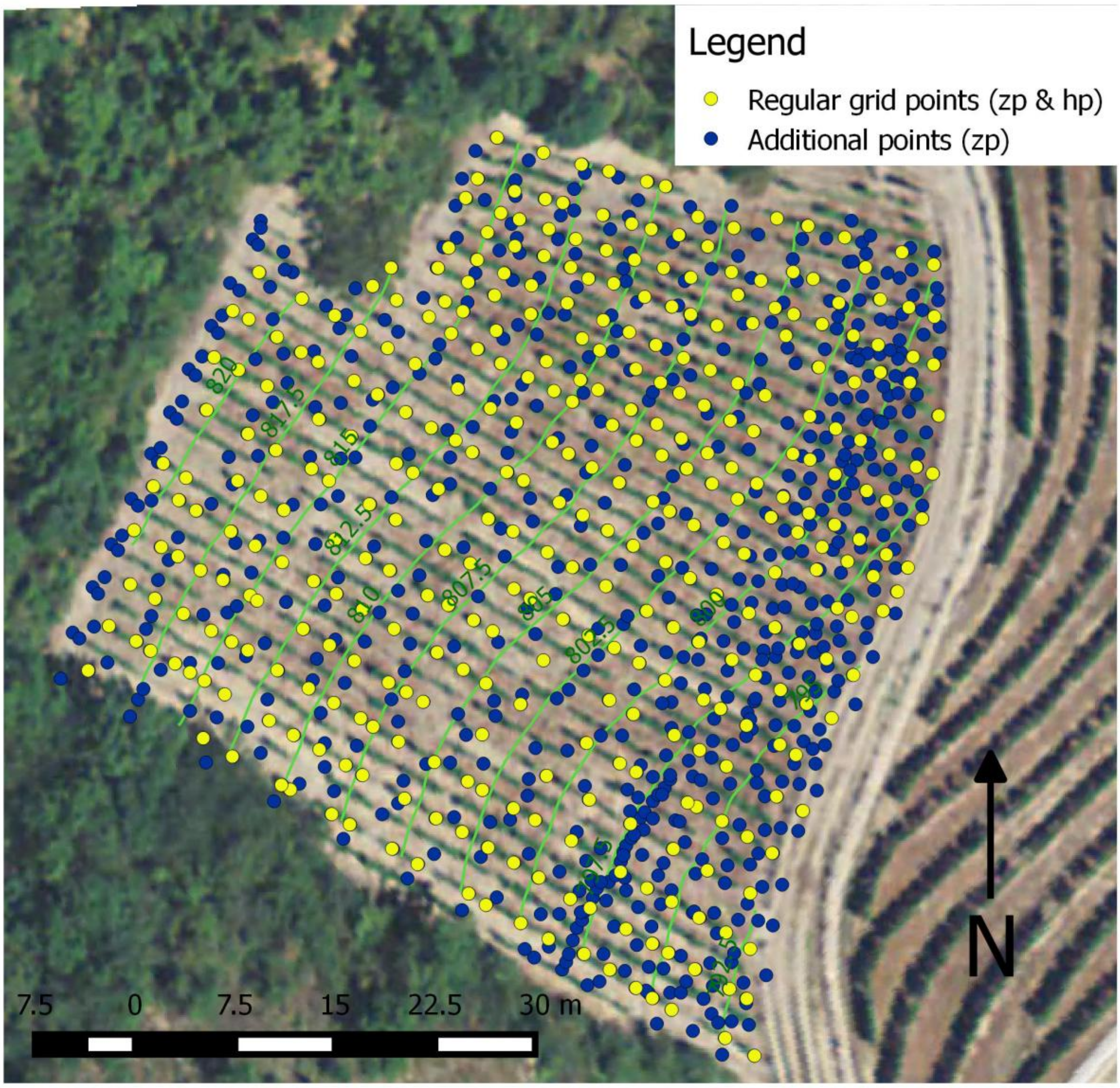


Figure 4 – Location of the points sampled during the topographical survey in the vineyards. Light (yellow) points indicates plants (n = 364) for which the present callus height was measured at the same moment of the topographical survey.

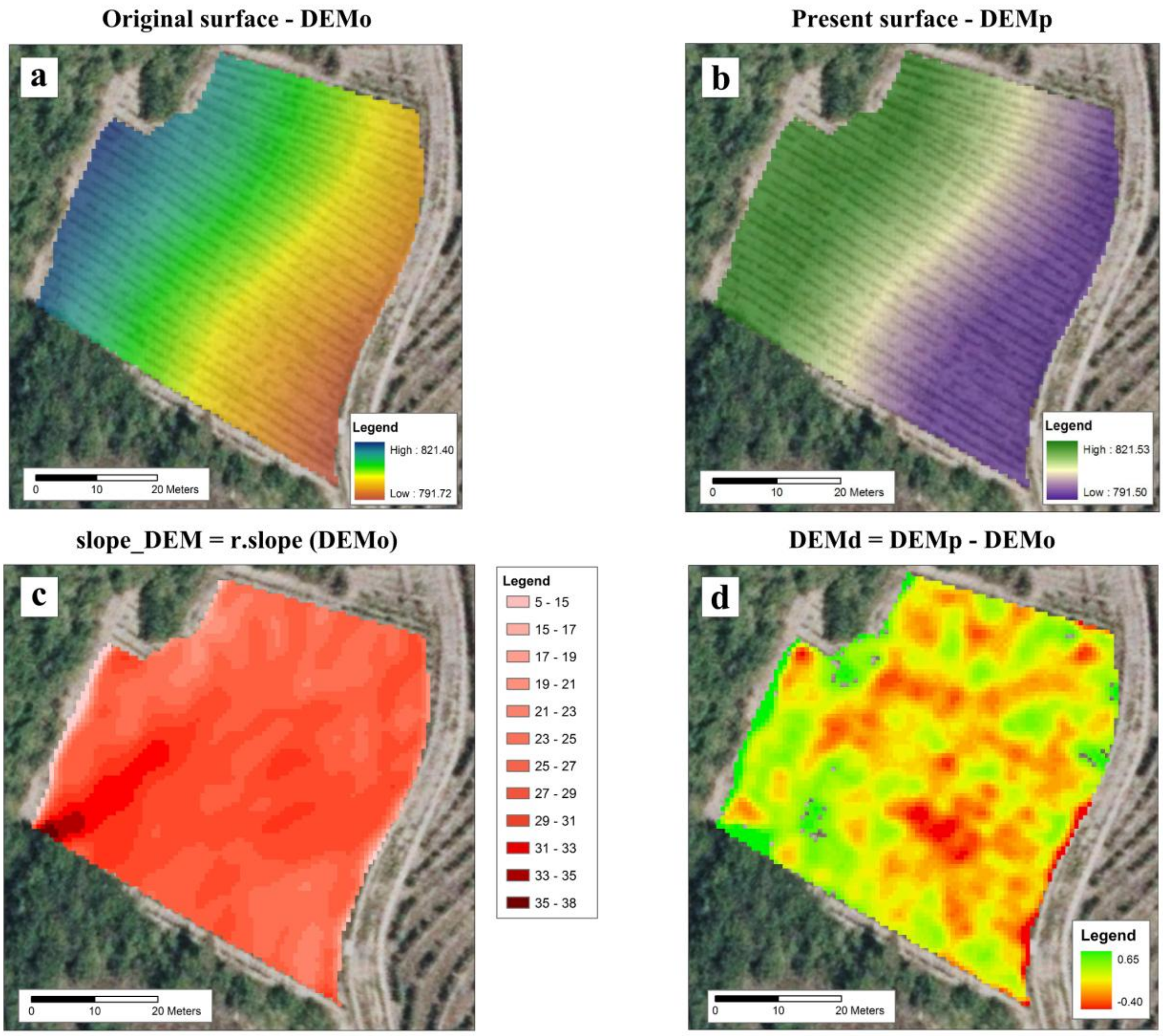
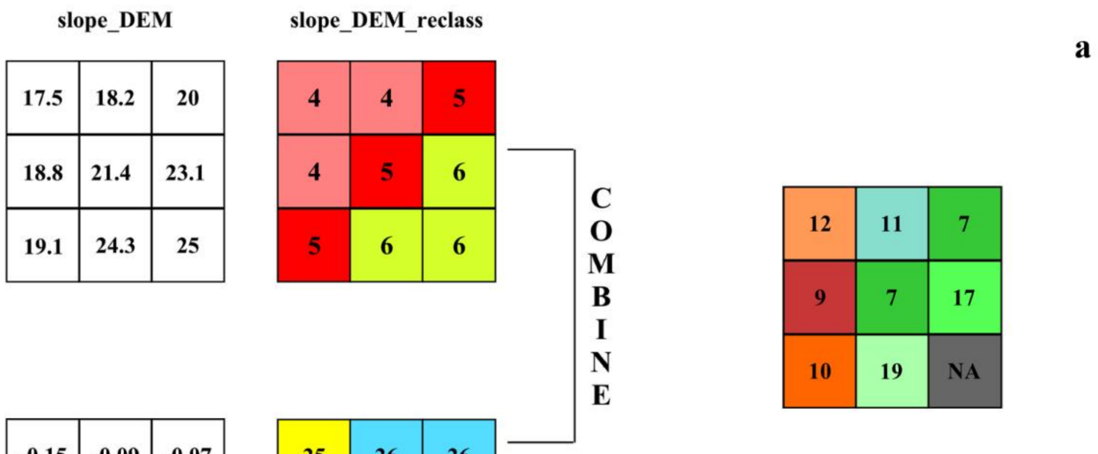
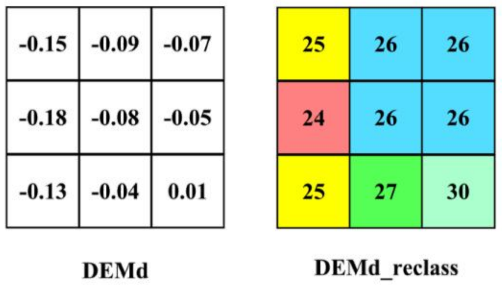


Figure 5 - DEMs of the original (DEMo, a) and present soil surface (DEMp, b), the slope map obtained from DEMo (slope_DEM, c) and the difference between DEMp and DEMo (DEMd, d).





slope_DEM_reclass	DEMd_reclass	VALUE	COUNT
...	...	...	...
4	25	12	72
4	26	11	89
4	27	6	53
4	28	34	9
4	29	NA	0
5	23	41	5
5	24	13	131
5	25	10	389
5	26	7	303
5	27	20	153
6	24	23	249
6	25	16	624
6	26	17	509
6	27	19	204
7	24	37	221
7	25	36	587
...	...	...	...

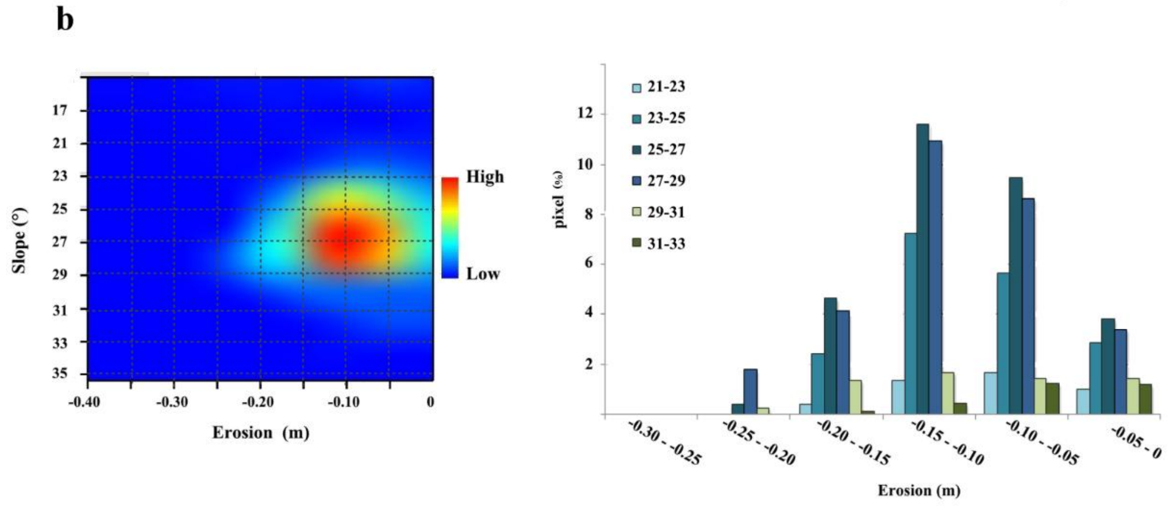


Figure 6 - (a) The schematic elaboration which was carried out, starting from the two rasters surface slope_DEM and DEMd, their reclassification and, finally the output of the combine operation between two rasters. The table is an extrapolation of the combine output. (b) Results of the combine operation, that show how erosion is distributed in cells of each class of slope. Histogram reports only significant results.

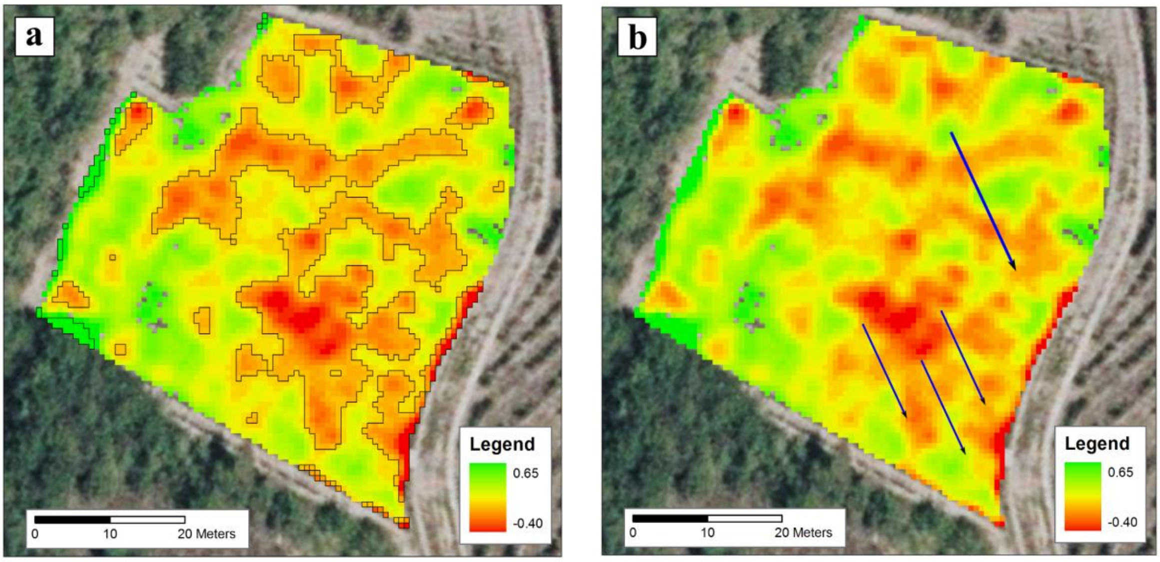


Figure 7 - Erosion maps, obtained from the DEMd, and taking in account ho=9.2 cm, both gross version and propagated error version (a, the black line delimits these areas), quantifying the soil losses (positive values) and gain (negative values) in meters over the vineyard surface during the vineyard entire life (1969-2013). On the right (b), the blue line indicates the main flow drainage direction obtained through the use of the morphological tool in GIS.