Pluri-decennial erosion rates using SUM/ISUM and sediment traps survey in the Mercurey vineyards (Burgundy, France)

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Highlights

- SUM/ISUM and sediment traps were used to estimate soil erosion on a vineyard sub-catchment
- The mean erosion rate on plots (SUM/ISUM) was 21.4 ± 3.1 $t.ha^{-1}.yr^{-1}$, but varied from −3.2 ± 1.5 $t.ha^{-1}.yr^{-1}$ to 53 ± 5.8 $t.ha^{-1}.yr^{-1}$.
- Sediment accumulation rates in traps varied from 16.6 ± 5.9 (upslope) to 0.13 ± 0.05 (downslope)
- The method was affected by error margins (from 7% to 43% of the measured value) that directly correlated with the erosion rate.
- Both topography (slope) and agricultural practices (backfilling) were identified as contributing factors of soil erosion.

Abstract

Vineyards are often considered to be among the agricultural lands most sensitive to erosion. We used the Stock Unearthing Measurement/Improved Stock Unearthing Measurement (SUM/ISUM) method and sediment traps volume measurements to assess the pluri-decennial erosion rates on a sub-catchment of the Mercurey vineyards in Burgundy, France. The measured erosion rates were compared to local environmental conditions (such as slope, soil type, age of vines, etc.) to discuss the role of driving factors. We found that the mean erosion rate was 21.4 ± 3.1 $t.ha^{-1}.yr^{-1}$ on vine plots (from −3.2 ± 1.5 $t.ha^{-1}.yr^{-1}$ to 53 ± 5.8 $t.ha^{-1}.yr^{-1}$), while sediment accumulation rates in traps varied from 16.6 ± 5.9 (upslope) to 0.13 ± 0.05 (outlet). The measurements were characterized by variable error margins (from 7% to 43% of the measured value) that are directly correlated with erosion rates. Both slope (USLE-LS factor) and age of vines were identified as driving factors of soil erosion. Runoff is the main modality of erosion. The higher erodibility of soil during the first years after plantation (unconsolidated and bare soil); and the regular (every 15 to 20 years) backfilling of eroded plots with soil collected in downslope sediment traps can explain the effect of the age of vines on erosion. In spite of erosion control strategies, the measured rates remain higher than what can be tolerated for sustainable development of agriculture. Therefore, we suggest that the current erosion mitigation strategy should be complemented with other techniques that maintain soils on plots (e.g., grass strips on the interrows, mulching).

1. Introduction

Vineyards are among the agricultural lands most sensitive to erosion (Kosmas et al., 1997; Cerdan et al., 2010; García-Ruiz et al., 2015). In French vineyards, measured erosion rates range from 10.5 to 54 $t.ha^{-1}.yr^{-1}$ (Viguier, 1993; Quiquerez et al., 2008; Paroissien et al., 2010; Prosdocimi et al., 2016). While erosion rates measured in Burgundy are of intermediate level, ranging from 14 to 23 $t.ha^{-1}.yr^{-1}$ (Brenot et al., 2008; Quiquerez et al., 2008; Fressard et al., 2017), they remain well above the average reference level of approximately 3 $t.ha^{-1}.yr^{-1}$ established for all agricultural activities (Cerdan et al., 2006), and values ranging from 0.3 to 1.4 $t.ha^{-1}.yr^{-1}$ established for soil sustainability (Verheijen et al., 2009). Beyond its direct impact on agricultural yield, the indirect consequences of this erosion threaten the sustainable exploitation of natural resources, causing mudflows, alteration of water quality, transfer of pesticides to rivers, and other consequences on ecosystem-services (eutrophication, biodiversity, carbon storage) (Greene et al., 1994; Pimentel et al., 1995; Lal, 1998; Hildebrandt et al., 2008; Rabiet et al., 2010).

Several methods have been developed and applied to measure soil erosion rates in vineyards. These methods are based on a wide variety of techniques and provide estimates of soil erosion at different spatial and temporal resolutions. Direct measurements have been conducted on experimental plots, especially to provide estimates of soil erosion rates under controlled or natural rainfall conditions in real in-field situations (Messer, 1980; De Figueiredo et al., 1998; Battany and Grismer, 2000; Arnaez et al., 2007; Biddoccu et al., 2016; Rodrigo-Comino et al., 2016a). Other techniques for indirect measurements are based on quantification of topographic changes to infer soil erosion. These methods aim to estimate the eroded volumes caused by rilling or gullying after high intensity rainfall events, doing so by using high resolution Digital Elevation Models (DEMs) obtained from in-field topographic surveys (Martínez-Casasnovas et al., 2002) or high resolution images taken before and after extreme events (Quiquerez et al., 2008; Remke et al., 2018). All of these techniques can provide measurements of erosion rates over relatively large areas (hillslope or small sub-catchment scale), but

71 can only be applied at very short time-scales (e.g., a few years), and cannot account for past erosion
72 processes. To provide information on multi-decennial timescales, radionuclides (Cs 137) have been
73 tested in vineyards (Loughran and Balog, 2006). This method can provide estimates of soil erosion, but
74 it is time consuming and is affected by large uncertainties (Boardman, 2006). Brenot et al. (2008)
75 developed a method called Stock Unearthing Measurement (SUM) that uses the vine stock graft union
76 as a passive marker of former topsoil level. This method allows estimation of eroded and accumulated
77 volumes by comparing the actual distance of the graft union from the ground with a known reference
78 level at the time of vineyard planting. The average erosion rate over multi-decennial timescales can
79 then be calculated, depending on the age of the vines (from 10 to 80 years). The SUM is simple to apply
80 and can provide results at the intra-plot scale with moderate error margins. This method was
81 successfully applied in various vineyards in Europe in the 2010s (Brenot et al., 2008; Casalí et al., 2009;
82 Paroissien et al., 2010b; Rodrigo-Comino et al., 2016a; Fressard et al., 2017). Rodrigo-Comino and
83 Cerdà (2018) proposed an improvement to the method called 'Improved Stock Unearthing
84 Measurement' (ISUM), which considers the fact that the interrows are often more incised than the
85 vine rows themselves. Consequently, a correction factor may be applied to correct former erosion
86 studies that used the SUM method.

87 Collectively, these studies help in the identification of factors contributing to soil erosion in vineyards:
88 topographic factors such as steep slopes (Rodrigo-Comino et al., 2017a), soil erodibility (Le Bissonnais
89 et al., 2006), rainfall erosivity (mostly extreme rainfall) (Martínez-Casasnovas et al., 2002; Quiquerez
90 et al., 2008; Ramos and Martínez-Casasnovas, 2009), and factors linked to agricultural practices such
91 as bare soils (Morvan et al., 2014; Napoli et al., 2017), slope oriented rows (Brenot et al., 2008), tillage,
92 and use of herbicides (Salome et al., 2014; García-Díaz et al., 2017). Additionally, Rodrigo-Comino et
93 al. (2018a) showed that the age of vines may influence the level of soil erosion, as terracing and tillage
94 conducted before the planting of new vines and during the first years of vine development increase
95 the sensitivity of soil to erosion. Following such studies, the specific roles of identified controlling
96 factors remain to be discussed and hierarchized.

One main scientific debate focuses on the consequences of the backfilling of ephemeral gullies, rills or full plots applied to compensate for soil loss. These practices have been documented in open field cultures in Belgium, and in vineyards in Spain, France, and Germany (Poesen, 1993; Martínez-Casasnovas et al., 2005; Quiquerez et al., 2008; Kirchhoff et al., 2017; Fressard et al., 2017). However, it remains difficult to estimate the precise level of compensation and the general role of these human interventions on soil erosion rates. Garcia et al. (2018) used detailed historical registries to provide estimates of anthropogenic compensations in burgundy during the middle-ages. Their study showed that backfilling (manual at that time) could return up to 9 $t.ha^{-1}.yr^{-1}$ of soils over time periods from 25 to 39 years. Nowadays, soil backfilling is no longer registered, and it is more difficult to get accurate quantification of anthropogenic practices. However, these practices are still applied, even though their role is not assessed and their efficiency few discussed.

In this paper, we contribute to the current debates on the evaluation of the role of specific local controlling factors on soil losses and more particularly on the role of anthropogenic practices (sediment backfilling). We focus on an intensive vineyard sub-region of burgundy, the Mercurey terroir. This sub-region is known for severe soil loss, and vine growers there have developed a collective strategy using sediment collectors and backfilling to mitigate soil loss and the transfer of particles to rivers (Fressard and Cossart, 2019). Using the SUM/ISUM method and volume measurements from sediment traps, we aimed to compare erosion rates between various physical settings, to hierarchize local controlling factors on pluri-decennial erosion rates.

2. Study area

2.1. Geomorphological context

The study area is located in the Mercurey terroir, which is part of the Burgundy wine region. The local geology consists of alternations of limestones and marly-limestones organized along tilted blocks dropping from west to east along eight main faults. At regional scale, this complex fault system consists in a contact area between the Morvan massif horst (west) and the Saône plain graben (east), (Fressard

et al., 2017). The Mercurey area is characterized by a 2 to 3 km-wide valley drained by the Giroux River, and is subdivided into eight sub-catchments. The measurements were conducted on the Monthelon sub-catchment, located in the northern part of Mercurey (Fig. 1). This sub-catchment is compact, and the global drainage direction is southerly. The vines are planted on gentle to moderately sloping gradients from 5° to 20°, and are surrounded by two steeper calcareous rocky ledges (30° to 40°) with an altitude difference of 15 to 25 m.

The mean annual precipitation is 770 $mm.yr^{-1}$, as measured by the Mercurey weather station (since 1971). The months of August and September are characterized by higher precipitation records than other months (80 mm on average) because of storm events and associated intense rainfall: 14 of the 18 storm events recorded from 1971 to 2018 (> 50 mm in one day) occurred during these two months.

All soils of the catchment are derived from the calcareous rocks that dominate the Mercurey area (limestone and marls). The most frequent soil type is calcosoil (FAO calcic cambisol), which develops on the marls. This soil type is characterized by varying degrees of stoniness (from 30% to 70%), with proximal ledges feeding the surface with scree and debris. These soils are of a moderate thickness (60 to 100 cm) and constitute the most frequent type of soil in the Mercurey vineyards. A slight variation in this soil can be observed on the north-west hillslope of the catchment where the upslope red oolitic limestone outcrop delivers a more reddish color to the ground surface (stoniness is also high, ranging from 30% to 60%, and depth is comparable to the most frequent soil type). On colluvial-deposit, soil profiles tend to be thicker (from 1 to 1.5m) still on calcic cambisoils. The limestone plateau surface is covered by rendisols (FAO rendzic leptosol). These soils are thin (less than 40 cm), are characterized by a lower carbonate content, and are rarely used for vine cultivation.

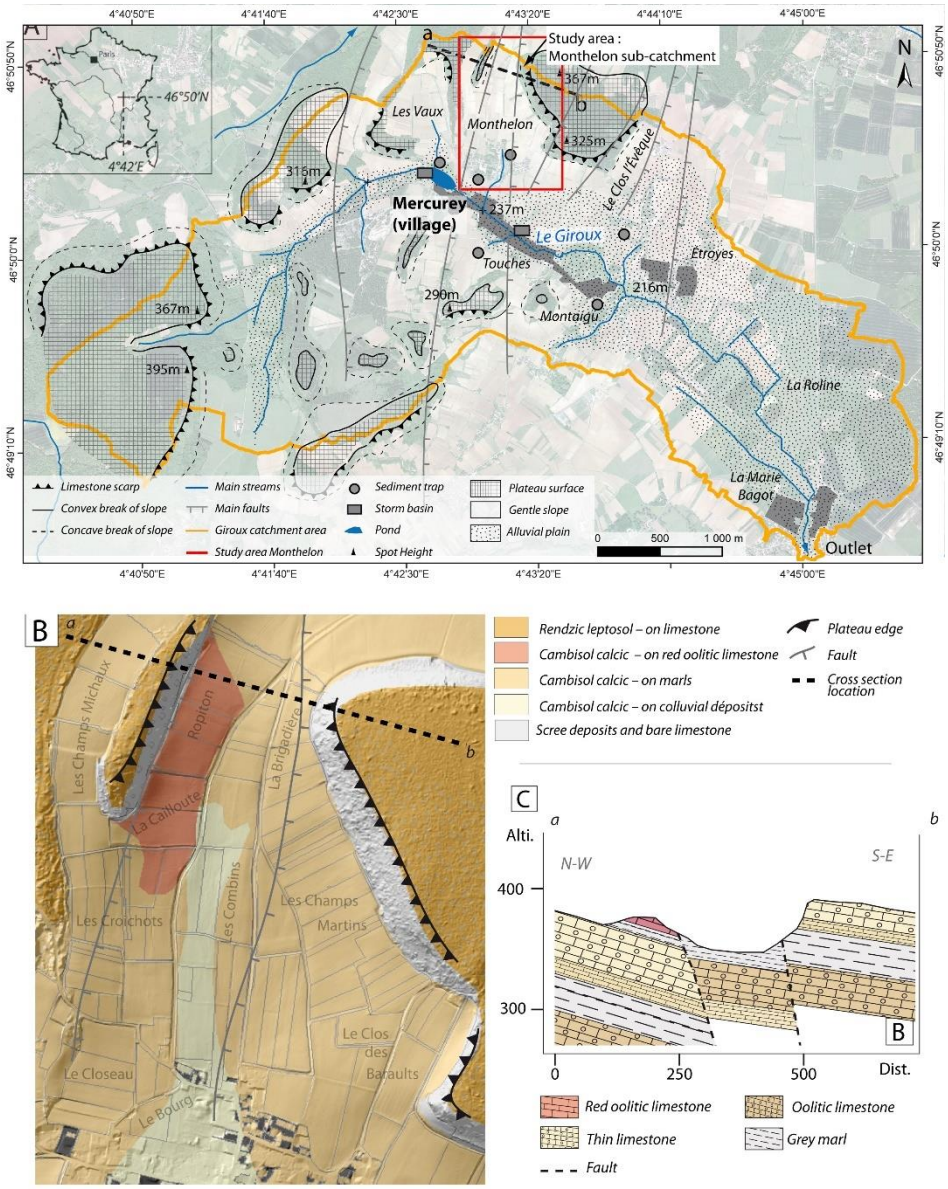


Figure 1: Location of the Monthelon sub-catchment and its pedo-geomorphological context. (A) Geomorphological sketch of the catchment, (B) soil map of the Monthelon sub-catchment, (C) geological cross section of Monthelon, and (D) global location in France.

2.2. Soil erosion management infrastructure and sediment collectors

After a significant phase of economic growth in the 1950s and 1960s, the initial patchwork of grassland and vineyards turned to almost a monoculture of vines (the surface area devoted to vineyards doubled after the second world war). Between 1948 and 1976, several hyperconcentrated flows occurred

following intense rainstorms (ungauged at that time), but it took the extreme events of 1981 and 1983 to raise collective awareness of the problem of soil erosion (Fressard et al., 2017; Cossart et al., 2021). The extreme flood of August 10, 1981 involved a record amount of rainfall (119.5 mm of rainfall in one day) and caused significant damages (destroying roads, flooding approximately 40 houses, and destroying harvests).

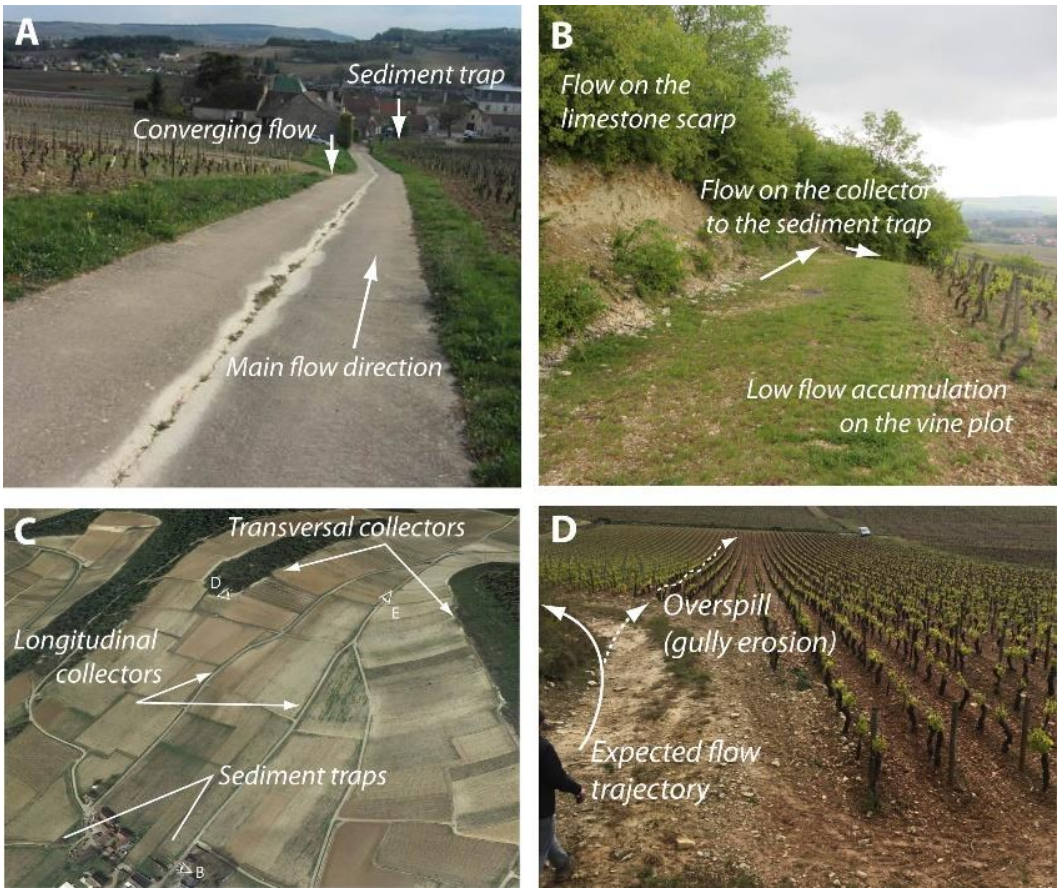


Figure 2: Examples of infrastructure collecting hydro-sedimentary fluxes on the Monthelon catchment. (A) Longitudinal collector, (B) transversal collector, (C) oblique aerial view of the catchment showing the organization of the collectors and ground locations, (D) example of overspill from a collector to a plot.

Figure 3: Illustrations of the backfilling strategy. (A) Sediment trap, (B) trapped sediments, (C) mechanical filling of parcels with trapped sediments, and (D) result of the backfilling on soil.

After another lower magnitude flood on the 12th of September 1983 (59 mm of rainfall in one day), an association was formed to bring together the grape growers of the Mercurey appellation with the objective of coordinating soil conservation and flood mitigation efforts. This association had two main goals: (1) to simplify the parcel pattern geometry, and (2) to take advantage of these simplifications to develop a network of hydraulic structures to collect and trap sediments. Three types of structures were built (Figs. 2 and 3) (Fressard and Cossart, 2019). First, on the upper slopes, a network of hedges and counter-slope paths were used to hamper the hydro-sedimentary flow between the plots and the upslope plateau edge. Second, ditches were constructed downstream to drain overflowing water and

sediments. The objective was to reduce runoff on plots in the middle of the slope, and thus limiting soil erosion. On the lower parts of the hillslopes, "V"-shaped concrete roads force the flow to converge towards the basins, in the direction of sediment traps (Fig. 2). The aim of these traps was to collect the sediments removed from the plots before they were exported to the Giroux River. If the sediments are thus captured, soil backfilling can be performed on the plots using the trapped sediments (Fig. 3). Interviews with the grape growers revealed that backfilling is generally performed every 15 to 20 years on sloping vineyards, and more frequently on areas (vine rows) specifically affected by gullies.

3. Methods

3.1. SUM measurements

3.1.1. General principle

The Stock Unearthing Method (SUM) developed by Brenot et al. (2006; 2008) has been widely used to estimate soil erosion in European vineyards (Brenot et al., 2008; Casalí et al., 2009; Paroissien et al., 2010a; Rodrigo-Comino et al., 2016, 2018a, 2018b). This method is based on the unearthing of the vine stock from the graft union, which is presumed to be spatially immobile in three dimensions. The graft union is thus considered a passive marker of soil erosion. Since the Phylloxera crisis in the 19th century, most European vines are grafted onto American stocks (underground roots), which are the only grape variety able to resist the pest. For agronomic reasons, the graft union point is systematically placed 1 or 2 cm above the ground when planting young vines. This *a priori* initial height is variable depending on bibliographical sources (e.g. 1 cm for Brenot et al., 2008 and 2 cm for Paroissien et al., 2010 and Rodrigo-Comino et al., 2018). The absolute position of this point is affected by a limited downwards shifting through time (Reynier, 2011) that has been quantified to be 0.2 mm.yr^{-1} by Brenot et al. (2008) for pinot noir varietal (varietal grown in Mercurey). Measurement of the distance between the graft union and the ground allows deduction of the ablation rate on each vine plant. By repetitively applying

this measurement on experimental plots, the method allows the spatial patterns of erosion dynamics to be estimated according to formula A:

$$ER = \frac{Vol \times D_s}{S_t \times A_v}$$

where, ER is the erosion rate expressed in $t.ha^{-1}.yr^{-1}$, Vol is the estimated eroded volume, D_s is the soil bulk density, S_t is the surface area, and A_v is the age of the vine plot.

3.1.2. ISUM corrections

The ISUM method (Rodrigo-Comino and Cerdà, 2018) involves the acquisition of measurements in the interrows, which are known to be more affected by erosion and tractor compaction. Additionally, the practice of ridging and un-ridging the vine rows is frequent in viticulture, and tends to artificially reduce the gap between the graft union and the ground on the vine row, whereas the interrow is artificially deepened. Measurements are conducted along a string stretched between two vine plants graft unions (or at a specific distance from the graft union on the plant) located on either side of the interrow (Fig. 4). This technique is very similar to that using erosion pin meters, which are widely used to measure soil roughness or to map gully erosion volumes (e.g. Casalí et al., 2006). Further details on the practical application of ISUM are provided in section 3.1.3.

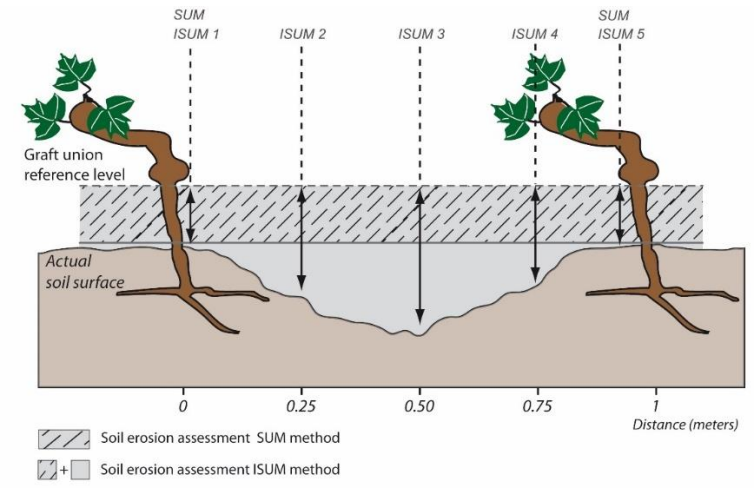


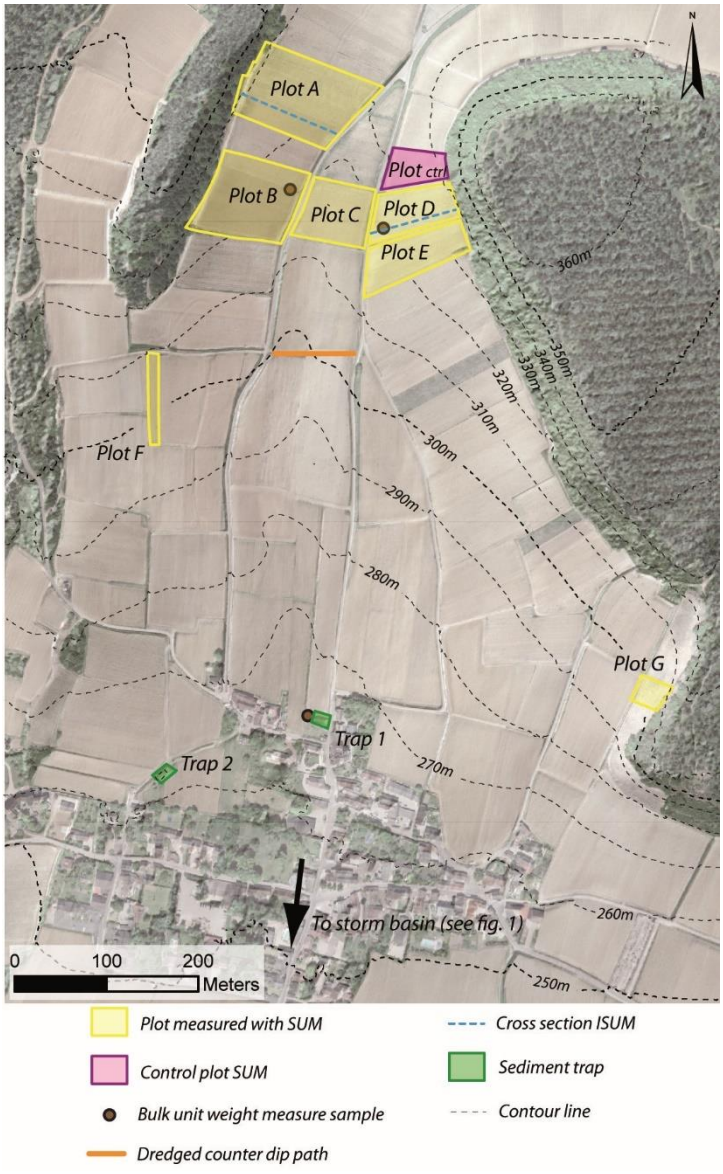
Figure 4: Illustration of the general principles of SUM and ISUM (after Brenot et al., 2008; and Rodrigo-Comino and Cerdà, 2018).

3.1.3. Field measurements and sampling strategy

We used the classical SUM method to measure 2359 vine plants over seven plots in the sub-catchment of Monthelon (plots referred to as A–G; Fig. 5), which consists in manually measuring with a ruler the distance between the graft union and the soil (given in cm with a 0.5 cm accuracy as suggested by Brenot et al., 2008). To minimize the errors that can arise from soil roughness (effect of tillage and stoniness), measurements were performed systematically on the downhill side of stocks and conducted in winter (as suggested by Brenot et al., 2008 and Paroissien et al., 2010). The main objective was to estimate the erosion rates on different types of parcels representing the diversity of the topographic characteristics of the area (steep to long and gentle slopes), as well as the various ages of the vine plants (from 9 to 42 years). In the investigated plots, measurements were made at a sampling distance of every 2 rows and every 3 plants in-row. This returned regular nodes on a griding of 3 x 3 m. The positions of all measured vine stocks were determined by differential GPS with a centimetric x, y, z accuracy. The z values (altitude) were not used for volumetric calculations as the GPS vertical accuracy (centimetric) is beyond what is requested by SUM.

To provide maps of the spatial distribution of erosion rates, we performed a spatial interpolation of the measured SUM values. For this, we selected the Topo to Raster function of ArcGIS, as it is often considered to be one of the best methods for working with topographic data (Zheng et al., 2016). The output cell size was set to 1 m, which is in good accordance with the accuracy of the initial data (grids of 3 m), and did not lead to excessive interpolation. Previous studies showed that other interpolation techniques (e.g. IDW, Kriging, EBK, RBFs) might also be suitable for deriving erosion surfaces (Rodrigo-Comino et al., 2019), but an accurate evaluation of them was considered beyond this study. Volume calculations (above and beyond the reference level - initial topsoil surface) were performed using the 3D analyst extension of ArcGIS to obtain the eroded and accumulated volume for each plot. The values were aggregated at the plot scale and the erosion volume was subtracted from the accumulation volume to obtain the net soil loss per plot. Finally, the values were reported relative to the surface

242 area (calculated using standard GIS tools), the age of vine (obtained from vine growers interview), and
243 bulk density of the soil (measured in sampling cylinders – see section 3.1.4), to calculate a mean specific
244 erosion rate expressed in $t.ha^{-1}.yr^{-1}$.



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246 Figure 5: Location of the field investigations conducted

247 ### *3.1.4. Estimation of the error margin*

248 In the SUM method, five main types of error can influence the final soil loss results: (1) imprecision in
249 the measurement of the space between the graft union and the ground; (2) variability of the distance
250 between the ground and graft union when the vine stock is planted; (3) variations in the bulk density

of soils; (4) errors in the interpolation of the surface raster used for volumetric calculations; and (5) the influence of the interrow morphology, as erosion tends to be more intense in the interrow than in the vine row (Rodrigo-Comino and Cerdà, 2018). To integrate such margins of error, additional data acquisitions were made.

To assess the direct effect of measurement error when a ruler is used, a set of 120 vine stocks were subjected to repeat measurements after a 6-hour time interval. Additionally, we took the opportunity to measure the distance between ground and graft union for a set of 99 vine stocks recently planted in a new vineyard within the study area. The main objective was to assess the accuracy of the distance from the graft union to the soil during vine stock planting. From these two sets of measurements, we used a standard error calculation to determine the 95% confidence interval according to the following formula (Altman and Bland, 2005):

$$e = 1.96\sqrt{\frac{\sigma}{n}}$$

where e is the confidence interval, 1.96 is a constant value obtained from the normal distribution table, σ is the standard deviation, and n is the sample size.

Considering independence and additivity principles on the error values, the planting error and the measurement error were combined using the quadratic sums of the individual terms.

$$e_{total} = \sqrt{e_{planting}^2 + e_{measure}^2}$$

A set of 12 samples were collected in the field using calibrated cylinders to measure the bulk density of the topsoil layer under different conditions. The two main types of soil were both sampled (four samples each), and additional samplings were performed on materials recently extracted from a sediment trap (Fig. 5). Mass calculations (volume × bulk unit weight) were performed for every plot using the minimum, maximum, and mean bulk density values, and these were added to the error margin extent.

Two test rows of vines were measured using the ISUM method. These rows were in two distinct plots characterized by contrasting agricultural practices: the presence or absence of ridging and un-ridging. During the field survey, two distinct types of vine row morphology (V-shaped and flat) were observed, and these were considered to be relevant to the investigation. We therefore conducted $ISUM_5$ measurements, which involved three additional points of measurements in the interrow. This resulted in a total of five points: two graft union measurements, one on either side, and three measurements in the interrow spaced at 25 cm, as the interrow length was 1 m. Higher resolution measurements were not considered, as comparative studies showed that a five-point ISUM is a good compromise between accuracy and the time required for field work (Rodrigo-Comino et al., 2019).

3.2. Volume estimation in sediment traps

The dredging of a sediment trap, a counter dip path, and a storm basin, offered the possibility to measure trapped volumes in four main points of the study area. The volumes were estimated by measuring the length, width, and height of earth mounds, and considering their shape as being pyramidal. The measured volumes were then related to the bulk unit weight, the last dredging date (obtained from the winegrowers association), and the upslope contributing area, to obtain the specific accumulation rate in the sediment collector/path. The values are expressed in $t.ha^{-1}.yr^{-1}$. We arbitrarily assumed a 10% error margin on the measurements made using this technique, which was added to the variability in the bulk unit weights obtained from laboratory analyses.

3.3. Comparing erosion rates with explanatory factors

To feed the discussion on potential driving factors of soil erosion, several available terrain parameters potentially contributing to soil erosion rates were compared to the measured values. The comparison was provided at the plot scale, based on a pairwise qualitative evaluation of the relationship between the driving factor and the measured erosion rates.

Slope angle was extracted from available Lidar DEM (1 m resolution) and plot length was calculated using standard GIS tools. The USLE LS factor (Wischmeier and Smith, 1978) was derived for each plot

using the mean slope angle and slope length using the Renard et al. (1997) equations. L factor can be represented as:

$$L = \left(\frac{\lambda}{22.13}\right)^{m}$$

where λ is the slope length (in meters) and m is equivalent to 0.5 for slopes steeper than 5%, 0.4 for slopes between 3%–4%, 0.3 for slopes between 1%–3% and 0.2 for slopes less than 1%.

The S factor can be represented as :

$$S = 10.8 \times \sin\theta, where\ slope\ gradient < 0.09$$

$$S = 16.8 \times \sin\theta, where\ slope\ gradient \geq 0.09$$

where Θ is the gradient of slope in radians.

Soil surface stoniness and soil type were derived from the available soil map and validated by field survey. The age of vine plots was also compared to the erosion rates as it has already been observed as a controlling factor of soil erosion rates in previous studies (Casali et al., 2009 ; Rodrigo-Comino et al., 2018a).

4. Results

4.1. Methods implementation for erosion assessment

4.1.1. Measurements and volume calculations

On the recently planted vineyard (<1 year-old) the mean measured plantation distance from the graft union to the ground was found to be 1.87 cm, with a standard deviation of 1.07 cm (Fig. 6). This returned a standard error of 0.11 and an error margin (accuracy of the mean) of 0.22. In addition, the SUM measurements repeated on the same stocks after a 6-hour interval returned a perfect match for 66% of measurements, with another 21.6% being within 1 cm. The final calculated error margin of the

measurement was 0.21 cm. Combining these two error margins returned a mean error of 0.33 cm per vine plant. Therefore, the volume calculations are systematically processed within this range (mean ± 0.33 cm).

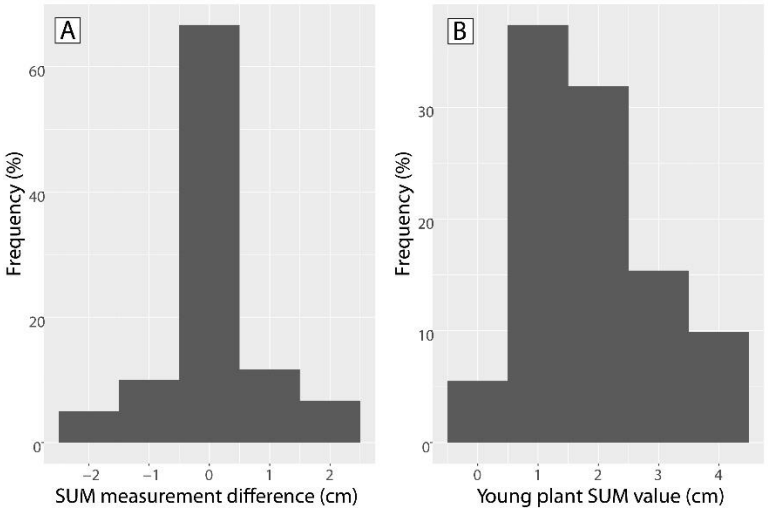
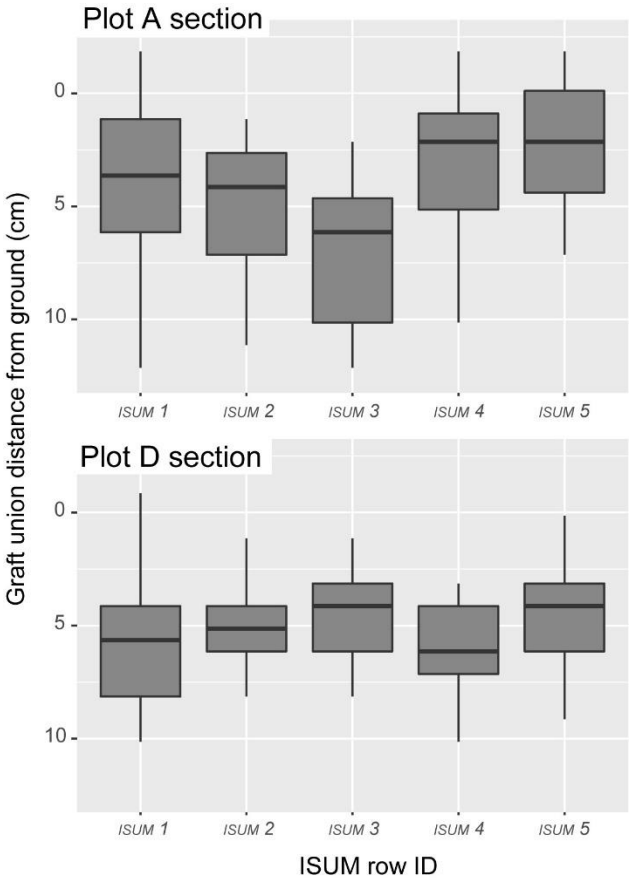


Figure 6: Distributions of the accuracy assessments of SUM difference (A) and measurement of young plants (B).

On plot B, the mean bulk density was 16.5 KN/m^3 (values ranged from 15.6 to 17.2), whereas on plot D it was 15.38 KN/m^3 (values ranged from 15.7 to 15.9). The bulk density of the material in the sediment trap was 13.8 KN/m^3 (values ranged from 13.6 to 14.3), and was lower because of the decompression of sediments due to transport and the absence of compaction by tractors. The conversion of eroded volumes to mass was therefore performed within the range of these measured values (mean, maximum, and minimum).

4.1.2. ISUM correction

The two test vine plots showed a variety of interrow conditions and morphology, which resulted in diverse ISUM correction factors. The ISUM section of plot A (Fig. 7) clearly shows a general V-shaped interrow morphology, which is contrary to the ISUM section of plot D, which shows a planar section between the row and interrow (Fig. 7).



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339 Figure 7: Boxplots of ISUM distribution over the two cross sections measured on plot A and plot D.

340 Reported to the initial top-soil level, vine row length, and width, the estimated erosion rates on these
341 two cross sections were 10.6 and 17.3 $t.ha^{-1}.yr^{-1}$ for section A using SUM and ISUM, respectively, and
342 58.2 and 58.3 $t.ha^{-1}.yr^{-1}$ for section D. These results indicate two main correction factors that can be
343 applied in regards to the interrow morphology. First, a correction factor of 40% can be considered in
344 the case of V-shaped interrows similar to those in plot A. Contrastingly, no correction factor need be
345 applied on plots characterized by a flat morphology (no deep incision affecting the interrow). Finally
346 on the basis of these field observations, a 40% ISUM correction factor was applied to results from plot
347 A, B, and F, whereas results from plots C, D, E, and G were not corrected.

348 **4.2. Soil erosion rates at the plot scale**

349 The mean soil loss measured on the seven plots was 21.4 ± 3.1 $t.ha^{-1}.yr^{-1}$. This average hides a wide
350 diversity of local situations (Figs. 8 and 9, Table 1). Plot A is characterized by a mean erosion rate of 10

± 2.2 $t.ha^{-1}.yr^{-1}$, which corresponds to a mean ablation of 0.5 ± 0.1 $mm.yr^{-1}$ over a measured timescale of 43 years. The mean slope gradient is 6.9°, the slope length is 118 m, LS factor is 3.5 and soil surface stoniness is between 35 to 40%. This plot shows higher erosion rates on the upslope part (south west) associated with a slight increase in slope gradient. Plot B has a mean erosion rate of 32.1 ± 4.5 $t.ha^{-1}.yr^{-1}$ (1.5 ± 0.1 $mm.yr^{-1}$). The mean slope is 10.2°, the plot length 89 m, LS factor is 5 and stoniness is between 35 to 40%. This plot is characterized by the presence of a small gully (± 30/40 cm deep and 1 m wide) on its north side, which significantly increases its mean erosion. It is developed on four vine rows on top, which converge together to form one unique row downslope. With the exclusion of the gully, the plot erosion rate drops to 15.8 ± 3.6 $t.ha^{-1}.yr^{-1}$, while the gully itself represents a mean erosion rate of 81.1 ± 5.7 $t.ha^{-1}.yr^{-1}$. Field observations showed that this gully originates from a dysfunction in the sediment collection system. A small local breach in the counter dip path creates an overspill of the accumulated flow directly into the plot, which drastically increases local runoff. Plot C is characterized by aggradation, as the measured erosion rate was −3.2 ± 1.5 $t.ha^{-1}.yr^{-1}$ (−0.2 ± 0.1 $mm.yr^{-1}$). The mean slope is 6.6° (the lowest gradient of all the slopes, but close to that of plot A), the length 77 m, LS factor is 2.7 and stoniness is between 30 to 35%. According to information obtained from interviews with the vine growers, this plot was recently backfilled (5 years ago), potentially contributing to its significant aggradation. Moreover, this plot is characterized by the lowest LS factor of the selected plots constituting also a context potentially less favorable to erosion. Plots D and E are affected by severe erosion rates of 43.1 ± 3.6 $t.ha^{-1}.yr^{-1}$ (3.5 ± 0.2 $mm.yr^{-1}$) and 53 ± 5.8 $t.ha^{-1}.yr^{-1}$ (4.7 ± 0.4 $mm.yr^{-1}$), respectively. These two plots have the highest LS factor (respectively 6.4 and 6.5), have a high stoniness (45 to 50%) and are the youngest measured in this study (15 and 9 years, respectively). The maps show a very regular pattern of erosion at the plot scale. Plot F was affected by an erosion rate of 10 ± 2.8 $t.ha^{-1}.yr^{-1}$ (0.5 ± 0.1 $mm.yr^{-1}$) over a timescale of 30 years. The mean slope is 9.1°, the plot length is 100 m, LS factor is 4.6 and stoniness is between 30 and 35%. The downslope part of the plot is slightly more affected by erosion than the upslope part. Plot G was affected by soil erosion of 4.6 ± 1.3 $t.ha^{-1}.yr^{-1}$ (0.3 ± 0.1 $mm.yr^{-1}$) over 37 years. The mean slope is 17.7°, the plot length 27 m. This plot is characterized

by a high LS factor of 5.1 (especially influenced by slope steepness while slope length is low) and a high stoniness (55 to 60%). Despite its steep slope and the absence of collecting infrastructure upslope (no counter dip path), this old vineyard is affected by a lower erosion rate than the other steep slopes plots.

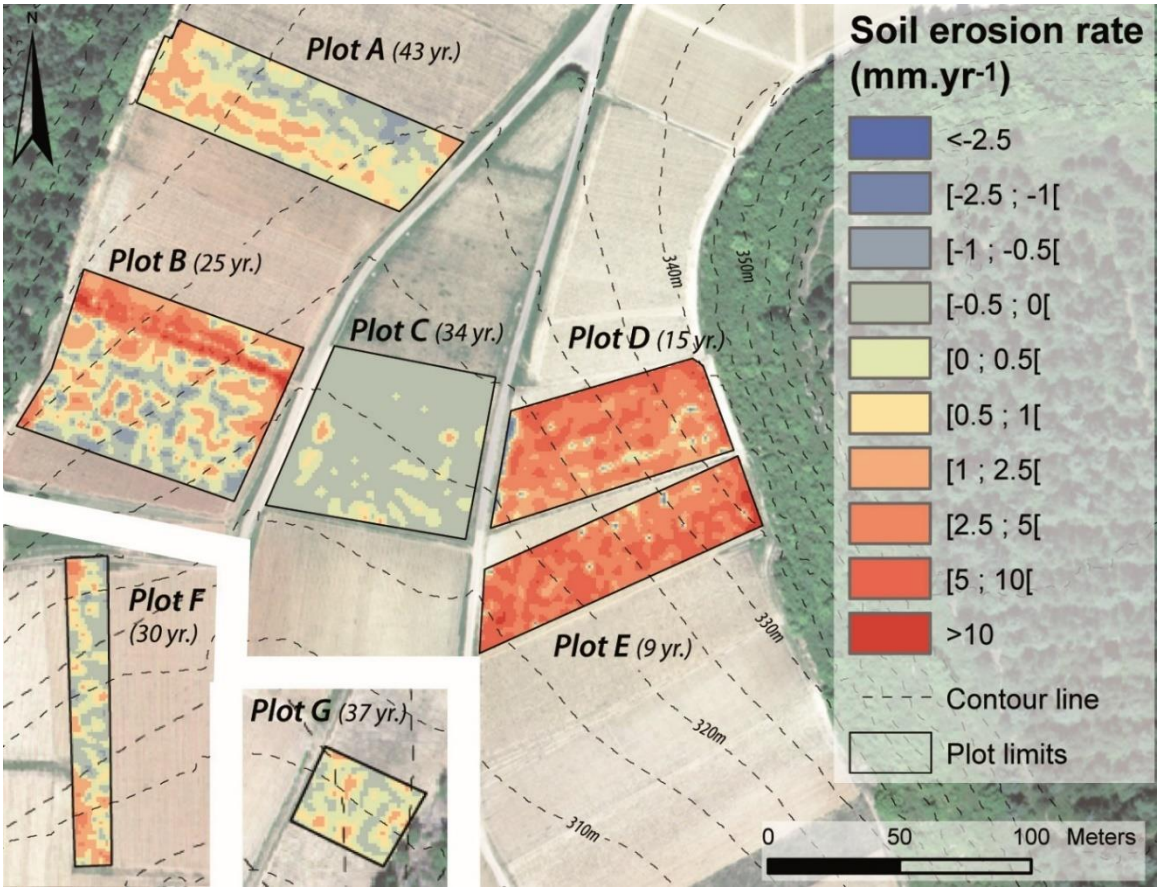


Figure 8: Erosion maps of the seven plots investigated

4.3. Comparison with potential driving factors

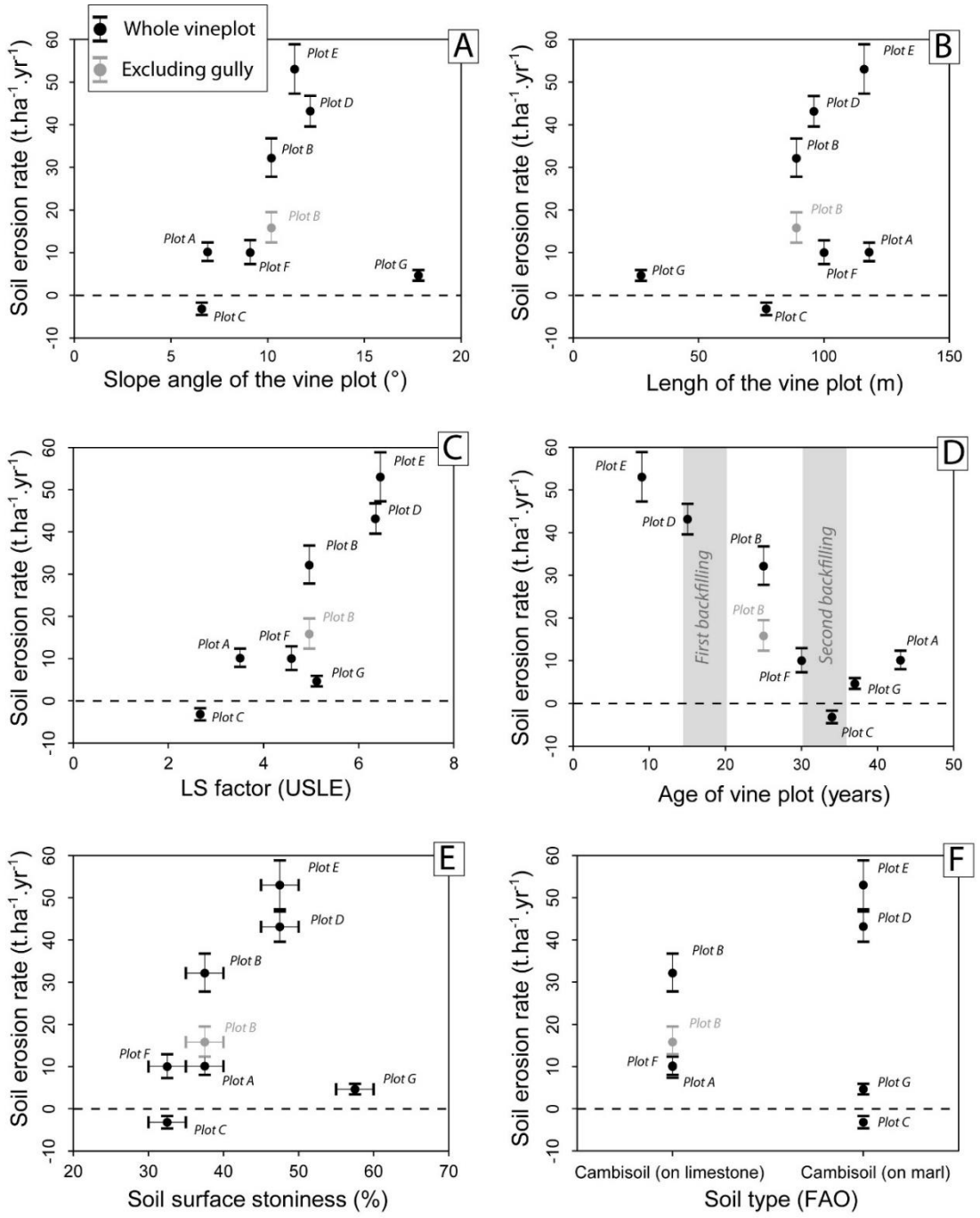
Unsurprisingly, we can notice an apparent link between topography and the soil erosion rate (fig. 9-A, B and C). Especially observing the correlation with the USLE LS factor (R^2 = 0.72). Plots characterized by low LS factors systematically show lower erosion: plots C and A exhibit LS factors below 4 and erosion rates below 10 $t.ha^{-1}.yr^{-1}$. On the opposite plots D and E exhibit high LS factor (above 6) and

high erosion rates, above 40 $t.ha^{-1}.yr^{-1}$. Plot G tends to be affected by a soil erosion lower than expected since in spite of a high LS factor (5.1) shows moderate soil erosion rate 4.6 ± 1.3 $t.ha^{-1}.yr^{-1}$.

Comparing the age of vines with soil erosion rates also shows a good correlation (Fig. 9-D, $R^2 = 0.79$). The two "young" (i.e., less than 15 years) vine plots (D and E) showed very high erosion rates above 40 $t.ha^{-1}.yr^{-1}$. Plot B, which is of an intermediate age (25 years), is characterized by a high to intermediate erosion rate of 15.8 ± 3.6 $t.ha^{-1}.yr^{-1}$ (excluding the gully), while the other vine plots (more than 30 years old) tend to show lower values (less than 10 $t.ha^{-1}.yr^{-1}$) or aggradation (plot C).

A relationship can be visually deduced between soil surface stoniness and soil erosion rates (even if R^2 is low: 0.11, fig. 9.E). Plots affected by higher erosion rates are characterized by a higher surface stoniness. This relationship appears counterintuitive since the soil surface stoniness is often considered having a negative effect on sediment yield and thus, can be considered as natural soil-surface stabilizer (e.g. Poesen and Ingelmo-Sánchez, 1992). In this case, it can be interpreted as a preferential export of fine sediments by runoff, increasing the coarse material fraction on plots affected by severe erosion. Only plot G can be seen as an exception in this case, which can be explained by the backfilling or by the proximity of the plateau edge which can efficiently feed soil surface with coarse elements.

No clear trend can be observed between the soil types and erosion rates as the plots appears unevenly distributed on fig. 9-F. This could be explained by homogeneity of soil types on the study area: both types of soils are Cambic calcic soils, which are only distinguished by the parent material marls and marly-limestone.



409

410 Figure 9: Measured erosion rates according to some explanatory factors. (A) slope angle, (B) slope

411 length, (C) USEL-LS factor, (D) age of vines, (E) soil surface stoniness and (F) soil type.

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4.4. Sub-catchment scale sediment transfer and connectivity

In the intermediate counter slope created by a transverse track, the trapped volume of sediments was quantified to be 30 ± 3 m^3 for a drained surface of 2.24 ha. These counter slopes are regularly dredged (every 1 to 2 years), depending on their filling rate. We measured the potential erosion over the period of a year to be 16.6 ± 5.9 $t.ha^{-1}.yr^{-1}$, which is of a comparable order of magnitude to the mean erosion measured on the parcels. On the two sediment traps located downslope of the catchment, the investigations performed by Fressard et al. (2019) allowed evaluation of an erosion rate of 1.31 ± 0.7 $t.ha^{-1}.yr^{-1}$ for trap one. A value of 0.15 ± 0.05 $t.ha^{-1}.yr^{-1}$ was assessed for the second trap, but this was affected by construction problems limiting its connectivity to the vine plots and its drainage efficiency. Finally, the sediment export rate measured in a storm basin connected to the main river of the catchment provided a result of 0.13 ± 0.05 $t.ha^{-1}.yr^{-1}$, which is much lower than the erosion rates measured on the vine plots, and the sediment traps and counter dip path of the upper slopes.

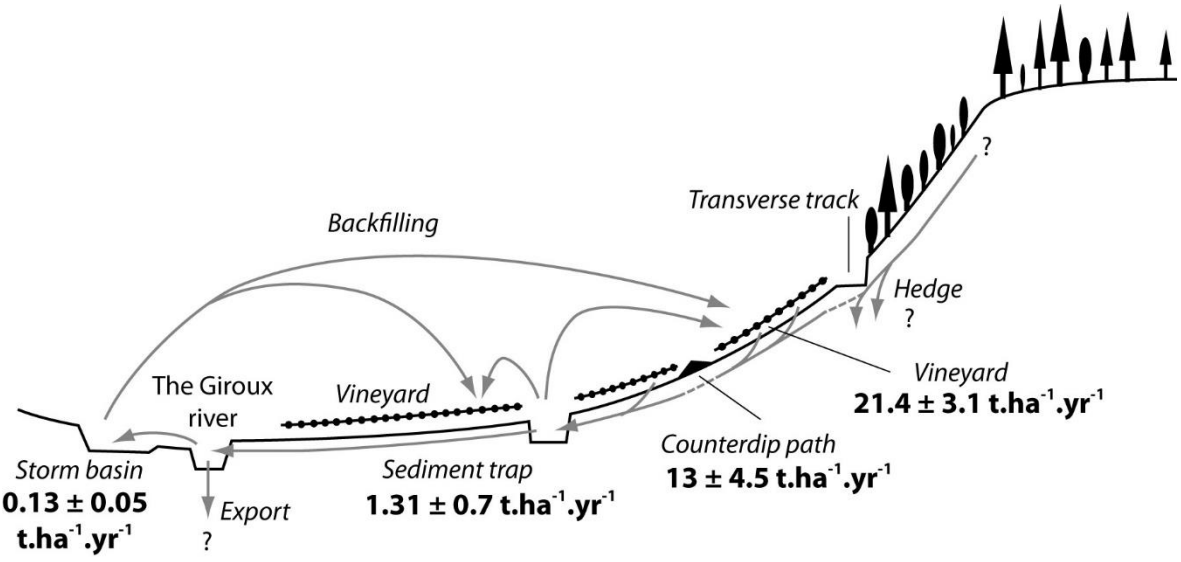


Figure 10: Sediment cascade in the Mercurey vineyards

From a general point of view, the specific erosion rates tend to decrease closer to the catchment outlet (Fig. 10). This observation is frequent in geomorphology, and it can be explained here by the effect of

landscape rugosity, the presence of anthropogenic counter slopes and traps, and the progressive decrease in slope gradient moving down the catchment. The contributing areas of the sediment traps and storm basin are wide (several hectares), favoring multiple intermediate sediment storage areas. This assumption can be easily confirmed in the field after intense storms, where numerous small sediment accumulations can be observed in various areas of the catchment (e.g., slope breaks between vine plots and roads, small diches, counter slopes, Fig. 11).

Table 1: Erosion rates at the plot scale

Plot	Age / timescale (yrs)	Area (ha)	Bulk unit weight (KN/m^3)	ISUM correction factor	Mean slope angle (°)	Slope length (m)	Surface lowering ($mm.yr^{-1}$)	Exported volume (m^3)	Exported mass (t.)	Soil loss ($t.ha^{-1}.yr^{-1}$)
A	43	0.41	16.5 ± 0.8	0.4	6.9	118	0.5 ± 0.1	77 ± 12.8	127.1 ± 27.3	10.1 ± 2.2
B	25	0.57	16.5 ± 0.8	0.4	10.2	89	1.5 ± 0.1	199.9 ± 18.3	329.9 ± 46.1	32.1 ± 4.5
B (gully area)	25	0.07	16.5 ± 0.8	0	10.2	89	6.2 ± 0.1	86 ± 1.8	142 ± 9.9	81.1 ± 5.7
B (ex. gully)	25	0.52	16.5 ± 0.8	0.4	10.2	89	0.8 ± 0.1	88.9 ± 15.7	146.7 ± 33	15.8 ± 3.6
C	34	0.46	15.8 ± 0.1	0	6.6	77	-0.2 ± 0.1	-31.7 ± 14.6	-50 ± 22.8	-3.2 ± 1.5
D	15	0.35	15.8 ± 0.1	0	12.2	96	3.5 ± 0.2	143.4 ± 11	226.5 ± 18.9	43.1 ± 3.6
E	9	0.33	15.8 ± 0.1	0	11.4	116	4.7 ± 0.4	98.6 ± 10.2	155.9 ± 17	53 ± 5.8
F	30	0.13	16.5 ± 0.8	0.4	9.1	100	0.5 ± 0.1	12.9 ± 3.9	27.8 ± 7.8	10 ± 2.8
G	37	0.06	15.8 ± 0.1	0	17.8	27	0.3 ± 0.1	4.5 ± 1.6	9.5 ± 2.6	4.6 ± 1.3
Counter dip path	1	2.50	13.8 ± 0.35	x	x	x	x	30 ± 3	41.4 ± 14.6	16.6 ± 5.9
S. trap 1	4	17.10	13.8 ± 0.35	x	x	x	x	65 ± 6.5	89.7 ± 31.7	1.31 ± 0.7
S. trap 2	28	16.50	13.8 ± 0.35	x	x	x	x	50 ± 5	69 ± 24.4	0.15 ± 0.05
Storm basin	28	300	13.8 ± 0.35	x	x	x	x	800 ± 80	1104 ± 390	0.13 ± 0.05

Figure 11: Deposition patterns observed in the field (A) deposition downslope a vine plot following a main runoff axis, (B) deposition in a ditch and (C) recently dredged deposition area on the downslope break of a vine plot

5. Discussion

5.1. Erosion rates and drivers observed in other vineyards using SUM and ISUM

Other studies have used the SUM technique to measure and map soil erosion at the plot scale. Globally, our measurements are consistent with those of Brenot et al. (2006, 2008), who measured values in Vosne-Romanée, Aloxe-Corton, and Monthélie ranging from 7.6 to 23 $t.ha^{-1}.yr^{-1}$ over timescales from 32 to 54 years. Brenot (2007) found a relationship between local topography (slope angle) and the level of soil erosion for slopes inferior to 10°. When slopes exceed this threshold, erosion rates appear to be function of the upslope area. Chevigny et al. (2014) have highlighted the role of historical

454 landscape structures (such as dry-stone walls) in the case of low erosion. In the case of severe erosion,
455 geomorphological drivers especially slope) dominate (runoff). Still in Burgundy, Quiquerez et al. (2014)
456 compared SUM measurements with DEMs and high resolution mapping of soil surface stoniness. Both
457 factors were found to be influential: higher erosion rates were observed on steeper slopes, while high
458 surface stoniness tends to reduce the erosion susceptibility. Rodrigo-Comino et al. (2017) directly
459 measured the effect of vineyard age on erosion and found a value of 62.5 $t.ha^{-1}.yr^{-1}$ for young vineyards
460 compared with 3.3 $t.ha^{-1}.yr^{-1}$ for old ones. A similar pattern was later confirmed by Rodrigo-Comino et
461 al. (2018a), ranging from 8.2 $t.ha^{-1}.yr^{-1}$ for young vineyards (2 years old) to 1.6 $t.ha^{-1}.yr^{-1}$ for old ones
462 (25 years). In these studies, the authors interpreted that most of the increase in the distance between
463 graft union and ground happens during the early years after plantation since unconsolidated soils are
464 more prone to erosion and compaction. Then, erosion rates get stabilized since compaction leads to a
465 lower sensitivity of soils. The same trend was observed by Casali et al. (2009) in Spain, with values of
466 36 to 50 $t.ha^{-1}.yr^{-1}$ for young plots versus 14 to 20 $t.ha^{-1}.yr^{-1}$ for older ones. In this study, the absence
467 of correlation between slope and erosion level was interpreted as a major role played by tillage erosion
468 that is sometimes considered among the most important driving factor of soil loss in agricultural lands
469 (e.g. Govers et al., 1999). Paroissien et al. (2010) measured a mean erosion of 10.5 $t.ha^{-1}.yr^{-1}$ in
470 Languedoc, with individual values ranging between −27.5 to 66.7 $t.ha^{-1}.yr^{-1}$. They found that slope
471 angle and the degree of connectivity (presence or absence of obstacles to runoff on the upslope of the
472 vine plot) showed direct relationships with the intensity of soil erosion.

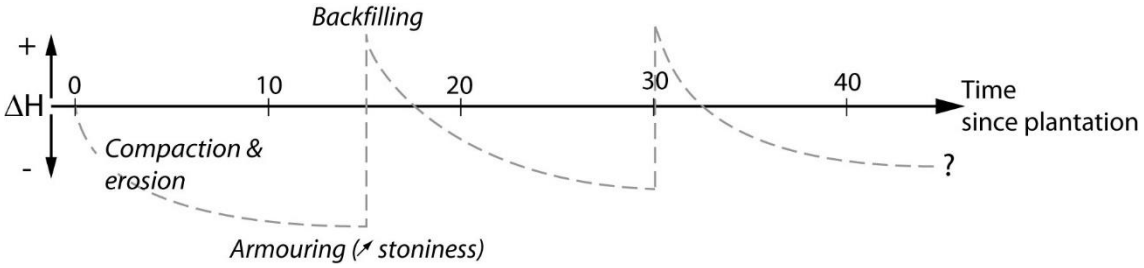
473

474 **5.2. The driving factors of erosion in Mercurey**

475 In the case of Mercurey, it can be stated that runoff plays a significant part in the erosion process, as
476 attested by several rill/gully shapes, fans downslope the plots and a good correlation between erosion
477 rates and USLE-LS factor. The regular (but not systematic) observation of a high degree of stoniness on
478 highly eroded slopes is a supplementary indicator of ongoing sheet wash erosion processes.

In addition, the specific practice that consists in backfilling eroded plots with collected soils should be accounted for in the sediment budget to explain the variations of erosion rates regarding the age of vines. This practice reveals a cyclicity in ground elevation variability within vine parcels, as documented by local vine growers. Three steps may be exhibited. First, terraced and deeply-tilled soils combined with low vegetation cover (young plants) are more sensitive to splash and runoff. In addition, tractor compaction is potentially very efficient on these still uncompacted soils: compaction rates (based on bulk density) ranging from 10% to 20% are often observed in various physical and anthropogenic settings (van Dijck and van Asch, 2002 ; Elaoud and Chehaibi, 2011 ; Botta et al., 2012). Although it remains difficult to assess the respective parts of erosion and compaction using the SUM/ISUM method, a rapid increase in the distance between the graft union and the soil is clear over the first years after plantation, and its measurement therefore integrates both processes. Local vine growers estimate that the stage of compaction generally lasts for 3 to 5 years (Fig. 12). After a period of 10 to 15 years, the plots show a significant decrease in erosion rate. A progressive reduction of soil erodibility does indeed occur in relation to soil compaction and progressive armoring of soils: erodible loamy soil particles are progressively exported and their stocks become exhausted. Then, soil surface stoniness increases.

Consequently, anthropogenic backfilling is performed. In Burgundy, vine-growers apply this strategy every 15 to 20 years, depending on the local situation. In the case of extreme morphogenic hydro-meteorological events, backfilling may occur more frequently. The objective of backfilling is to compensate for soil losses by adding an external supply of soil, providing earth material to cover the graft-union. Therefore, in old vineyards, the measured erosion rates (considering the time elapsed since plantation) may reveal an apparent equilibrium. The results obtained on the oldest vineyards in Mercurey (plots A and G) do indeed show that the erosion rates stabilized at between roughly 4.5 to 10 $t.ha^{-1}.yr^{-1}$ over long time periods (many decades). However, these values remain much higher than the estimated tolerable erosion rates for sustainable development of agriculture (Verheijen et al., 2009).



505

506 Figure 12: Cyclicity in ground elevation in vine parcels. The succession of three main stages is exhibited:
507 compaction, armoring, and backfilling.

508

509 On the one hand, anthropogenic backfilling can appear to be an efficient strategy to cope with soil
510 losses, but on the other hand, it can also be considered a resetting of sediment sources. Recent
511 observations of flash floods following intense rainstorms revealed high concentrations of suspended
512 particles, suggesting that vine parcels remain a significant source of sediments. Large amounts of fine
513 particles are still supplied and exported from the catchment, despite the sediment trapping system.
514 Further research is needed to accurately estimate the efficiency of trapping systems, especially on fine-
515 size particles.

516

517 **5.1. Methodological feedback and error margins**

518 In this study, the estimated cumulative error margins associated with (1) manual measurement of the
519 height, (2) vine plantation accuracy, and (3) soil bulk unit weight estimation are variable (from 7% to
520 45% of the final estimated value in $t.ha^{-1}.yr^{-1}$). The error margin is a direct function of the intensity of
521 observed erosion, and tends to be less influential in the case of high-level erosion (fig. 13). Then, more
522 than the age of vines, the level of erosion is the most influential factor on the error. Therefore, the
523 measurements of plots affected by erosion rates of less than 10 $t.ha^{-1}.yr^{-1}$ must be interpreted with
524 caution as the error margin might exceed 25%. Nevertheless, the approach still allows provision of the
525 overall order of magnitude of the intensity of erosion, even if lower erosion rates are affected by more

uncertainty. The studies of Brenot et al. (2008), Chevigny et al. (2014) and Quiquerez et al. (2014) explicitly expressed the final estimated erosion rate within the error margin range and allow comparison. In these articles, error margins that includes plantation, measurement errors and bulk unit weight were found to be between 20 to 40%. Other studies (e.g. Casalí et al., 2009 ; Paroissien et al., 2010 ; Rodrigo-Comino et al., 2016) also assessed the error. They conclude that in spite of the error margin the method is still applicable, given that the overall soil loss is much higher than the experimental error.

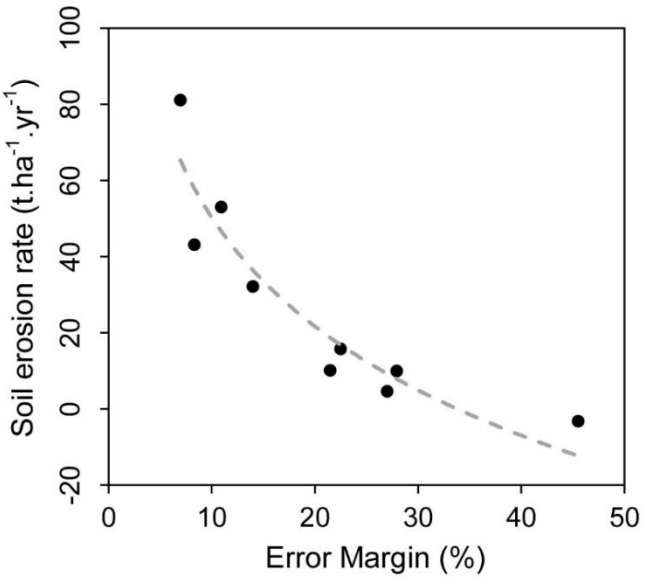


Figure 13: Relationship between the soil erosion rate and error margin

The repeatability of a vine stock measurement in the field is among the factors that tends to increase the error margins. This error is mostly due surface roughness and stoniness that can make the graft union height measurement difficult. We applied standardized techniques already published to make comparison easier (Brenot et al., 2008; Paroissien et al., 2010). The imprecisions of the graft union height at plantation is also a source of uncertainty that can not be avoided. The measurement of a control plot (recently planted vineyard) allowed estimating a standard deviation of 1.07 cm (standard error 0.22) which is in good agreement with findings of Brenot et al. (2006, 2008) and Paroissien et al.

(2010) who found a value of 1 cm. Casalí et al. (2009) found a value of 2 cm. Bulk unit weight is also a source if variability in the final conversion of the results from volume to mass that is not systematically measured (this parameter is often deduced from bibliographic review and set between 12.5 to 15 KN/m^3). In our study, we used a total of 12 samples for bulk unit weight calculations separated in 2 types of soils and sediments accumulated in traps. The use of more points of control (several measurements per plot at different depth) may improve slightly the estimate of erosion.

The ISUM correction factor, which was first applied to Spanish vineyards by Rodrigo-Comino and Cerdà (2018), was shown to be of relevance to our case study. However, the diversity of the interrow morphologies also demonstrates that this technique should be applied with caution, and the correction factor was differently applied according to the interrow morphology and field expertise. In this case study, the ISUM correction value for three plots was 40%, which is much higher than the 25.7% proposed by Rodrigo-Comino and Cerdà (2018) for Spanish vineyards. However, four plots were characterized by a correction factor of 0%. This approach is more accurate than the traditional SUM method, but extents the data acquisition time in the field (between 1.5 to 2 times longer on the basis of our experience). Therefore, it remains more difficult to deploy the ISUM method over large areas. Our estimate of the ISUM correction factor is, in this case study, only based on two rows. A larger application of the comparison and also higher resolution measurements in the interrow might help increase the accuracy of the correction factor, which may vary from plot to plot, even on the same catchment and with relatively similar agricultural practices.

The comparison of long-term soil erosion on vine plots with short-term measurements in sediment traps and the counter dip path (i.e., 1 to 4 years) allowed a general assessment of the order of magnitude of erosion, but this assessment still remains difficult. The short-term measurements may be affected (positively or negatively) by the presence or absence of extreme events that may bias the approach. In this sense, regular monitoring of sediment traps and other sediment sinks within the catchment may be of great interest for detailing the sediment budget.

568 Finally, this method is based on the pluri-decennial assessment of the total exported volume and thus
569 integrates all anthropogenic actions that can be conducted on plots. Tractor compaction, tillage
570 erosion, backfilling and eventually application of organic fertilizers (rare in Burgundian vineyards) are
571 implicitly accounted when measuring the erosion rate. In that sense, comparing the measured erosion
572 rates with a detailed modelling might be a future perspective to assess the respective part of direct
573 anthropogenic actions and natural processes (runoff) within the observed erosion rate.

574

575 ## 6. Conclusions

576 We used the SUM/ISUM measurement technique to estimate pluri-decennial soil erosion rates on
577 seven experimental plots in the Mercurey region of Burgundy. The mean erosion rate was 21.4 ± 3.1
578 $t.ha^{-1}.yr^{-1}$, but varied substantially from −3.2 ± 1.5 $t.ha^{-1}.yr^{-1}$ to 53 ± 5.8 $t.ha^{-1}.yr^{-1}$. A variable ISUM
579 correction factor was applied, depending on the interrow morphology, which is directly influenced by
580 the vine growers' practices (e.g., the presence or absence of tillage and ridging/un-ridging of the vine
581 rows). The SUM/ISM was complemented by volumes measurements in sediment traps and in a counter
582 dip path. A decreasing trend of the specific erosion rate was observed along hillslopes (upslope to
583 downlope) (from 16.6 ± 5.9 in the most upstream counter dip path to 0.13 ± 0.05 in a storm basin
584 downstream). The results were complemented by an assessment of error margins, that are ranging
585 from 7% to 43%. Such values are directly correlated with the erosion rate: the higher the erosion rate,
586 the lower the error margin.

587 Hillslope erosion appears to be controlled by runoff (rill, inter-rill). Age-related differences in the level
588 of soil erosion has been observed and can originate from (1) the higher sensitivity of soil during the
589 first years after plantation (unconsolidated and bare soil), which tends to be reduced after a few years
590 (canopy development and tractor compaction); and (2) more specific to Burgundy, the regular (every
591 15 to 20 years) backfilling of eroded plots with soil collected in downslope sediment traps. Spatial
592 variability of erosion illustrates the effect of sediment connectivity and the efficiency of man-made

infrastructures to store eroded sediments from plots and hamper sediment transfer to rivers (landscape rugosity, slope breaks between vine plots and roads, small diches, counter slopes, sediment traps, etc.). In addition, Despite this technique, the erosion rates remain high (especially on vine plots), and suggest that backfilling from sediment traps should be combined with other soil erosion mitigation techniques that maintain soils on plots (e.g., grass strips on the interrow, mulching), taking action on the source area rather than managing its consequences.

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