

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

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Mathieu Fressard, Etienne Cossart, Brian Chaize. Pluri-decennial erosion rates using SUM/ISUM and sediment traps survey in the Mercurey vineyards (Burgundy, France). Geomorphology, 2022, 403, pp.108181. 10.1016/j.geomorph.2022.108181. hal-03767503

HAL Id: hal-03767503 https://hal.science/hal-03767503

Submitted on 2 Sep 2022

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1	Pluri-decennial erosion rates using SUM/ISUM and sediment traps										
2	survey in the Mercurey vineyards (Burgundy, France)										
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7	69007, France.										
8	Highlights										
9	- SUM/ISUM and sediment traps were used to estimate soil erosion on a vineyard sub-catchment										
10	- The mean erosion rate on plots (SUM/ISUM) was 21.4 \pm 3.1 t.ha ⁻¹ .yr ⁻¹ , but varied from –3.2 \pm 1.5										
11	t.ha ⁻¹ .yr ⁻¹ to 53 ± 5.8 t.ha ⁻¹ .yr ⁻¹ .										
12	- Sediment accumulation rates in traps varied from 16.6 ± 5.9 (upslope) to 0.13 ± 0.05 (downslope)										
13	- The method was affected by error margins (from 7% to 43% of the measured value) that directly										
14	correlated with the erosion rate.										
15	- Both topography (slope) and agricultural practices (backfilling) were identified as contributing										
16	factors of soil erosion.										
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22 Abstract

23 Vineyards are often considered to be among the agricultural lands most sensitive to erosion. We used 24 the Stock Unearthing Measurement/Improved Stock Unearthing Measurement (SUM/ISUM) method 25 and sediment traps volume measurements to assess the pluri-decennial erosion rates on a sub-26 catchment of the Mercurey vineyards in Burgundy, France. The measured erosion rates were 27 compared to local environmental conditions (such as slope, soil type, age of vines, etc.) to discuss the 28 role of driving factors. We found that the mean erosion rate was $21.4 \pm 3.1 \text{ t.ha}^{-1}$.yr⁻¹ on vine plots 29 (from $-3.2 \pm 1.5 \text{ t.ha}^{-1}.\text{yr}^{-1}$ to $53 \pm 5.8 \text{ t.ha}^{-1}.\text{yr}^{-1}$), while sediment accumulation rates in traps varied 30 from 16.6 \pm 5.9 (upslope) to 0.13 \pm 0.05 (outlet). The measurements were characterized by variable 31 error margins (from 7% to 43% of the measured value) that are directly correlated with erosion rates. 32 Both slope (USLE-LS factor) and age of vines were identified as driving factors of soil erosion. Runoff is 33 the main modality of erosion. The higher erodibility of soil during the first years after plantation 34 (unconsolidated and bare soil); and the regular (every 15 to 20 years) backfilling of eroded plots with 35 soil collected in downslope sediment traps can explain the effect of the age of vines on erosion. In spite 36 of erosion control strategies, the measured rates remain higher than what can be tolerated for 37 sustainable development of agriculture. Therefore, we suggest that the current erosion mitigation 38 strategy should be complemented with other techniques that maintain soils on plots (e.g., grass strips 39 on the interrows, mulching).

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46 **1. Introduction**

47 Vineyards are among the agricultural lands most sensitive to erosion (Kosmas et al., 1997; Cerdan et 48 al., 2010; García-Ruiz et al., 2015). In French vineyards, measured erosion rates range from 10.5 to 54 49 t.ha⁻¹.yr⁻¹ (Viguier, 1993; Quiquerez et al., 2008; Paroissien et al., 2010; Prosdocimi et al., 2016). While 50 erosion rates measured in Burgundy are of intermediate level, ranging from 14 to 23 t.ha⁻¹.yr⁻¹ (Brenot 51 et al., 2008; Quiquerez et al., 2008; Fressard et al., 2017), they remain well above the average reference 52 level of approximately 3 t.ha⁻¹.yr⁻¹ established for all agricultural activities (Cerdan et al., 2006), and 53 values ranging from 0.3 to 1.4 t.ha⁻¹.yr⁻¹ established for soil sustainability (Verheijen et al., 2009). 54 Beyond its direct impact on agricultural yield, the indirect consequences of this erosion threaten the 55 sustainable exploitation of natural resources, causing mudflows, alteration of water quality, transfer 56 of pesticides to rivers, and other consequences on ecosystem-services (eutrophication, biodiversity, 57 carbon storage) (Greene et al., 1994; Pimentel et al., 1995; Lal, 1998; Hildebrandt et al., 2008; Rabiet 58 et al., 2010).

59 Several methods have been developed and applied to measure soil erosion rates in vineyards. These 60 methods are based on a wide variety of techniques and provide estimates of soil erosion at different 61 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 62 63 real in-field situations (Messer, 1980; De Figueiredo et al., 1998; Battany and Grismer, 2000; Arnaez et 64 al., 2007; Biddoccu et al., 2016; Rodrigo-Comino et al., 2016a). Other techniques for indirect 65 measurements are based on quantification of topographic changes to infer soil erosion. These 66 methods aim to estimate the eroded volumes caused by rilling or gullying after high intensity rainfall 67 events, doing so by using high resolution Digital Elevation Models (DEMs) obtained from in-field 68 topographic surveys (Martínez-Casasnovas et al., 2002) or high resolution images taken before and 69 after extreme events (Quiquerez et al., 2008; Remke et al., 2018). All of these techniques can provide 70 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.

97 One main scientific debate focuses on the consequences of the backfilling of ephemeral gullies, rills or 98 full plots applied to compensate for soil loss. These practices have been documented in open field 99 cultures in Belgium, and in vineyards in Spain, France, and Germany (Poesen, 1993; Martínez-100 Casasnovas et al., 2005; Quiquerez et al., 2008; Kirchhoff et al., 2017; Fressard et al., 2017). However, 101 it remains difficult to estimate the precise level of compensation and the general role of these human 102 interventions on soil erosion rates. Garcia et al. (2018) used detailed historical registries to provide 103 estimates of anthropogenic compensations in burgundy during the middle-ages. Their study showed 104 that backfilling (manual at that time) could return up to 9 t.ha⁻¹.yr⁻¹ of soils over time periods from 25 105 to 39 years. Nowadays, soil backfilling is no longer registered, and it is more difficult to get accurate 106 quantification of anthropogenic practices. However, these practices are still applied, even though their 107 role is not assessed and their efficiency few discussed.

108 In this paper, we contribute to the current debates on the evaluation of the role of specific local 109 controlling factors on soil losses and more particularly on the role of anthropogenic practices 110 (sediment backfilling). We focus on an intensive vineyard sub-region of burgundy, the Mercurey 111 terroir. This sub-region is known for severe soil loss, and vine growers there have developed a 112 collective strategy using sediment collectors and backfilling to mitigate soil loss and the transfer of 113 particles to rivers (Fressard and Cossart, 2019). Using the SUM/ISUM method and volume 114 measurements from sediment traps, we aimed to compare erosion rates between various physical 115 settings, to hierarchize local controlling factors on pluri-decennial erosion rates.

- **2. Study area**
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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 129 1971). The months of August and September are characterized by higher precipitation records than 130 other months (80 mm on average) because of storm events and associated intense rainfall: 14 of the 131 18 storm events recorded from 1971 to 2018 (> 50 mm in one day) occurred during these two months.

132 All soils of the catchment are derived from the calcareous rocks that dominate the Mercurey area 133 (limestone and marls). The most frequent soil type is calcosoil (FAO calcic cambisol), which develops 134 on the marls. This soil type is characterized by varying degrees of stoniness (from 30% to 70%), with 135 proximal ledges feeding the surface with scree and debris. These soils are of a moderate thickness (60 136 to 100 cm) and constitute the most frequent type of soil in the Mercurey vineyards. A slight variation 137 in this soil can be observed on the north-west hillslope of the catchment where the upslope red oolitic 138 limestone outcrop delivers a more reddish color to the ground surface (stoniness is also high, ranging 139 from 30% to 60%, and depth is comparable to the most frequent soil type). On colluvial-deposit, soil 140 profiles tend to be thicker (from 1 to 1.5m) still on calcic cambisoils. The limestone plateau surface is 141 covered by rendisols (FAO rendzic leptosol). These soils are thin (less than 40 cm), are characterized 142 by a lower carbonate content, and are rarely used for vine cultivation.

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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.

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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.

167 After another lower magnitude flood on the 12th of September 1983 (59 mm of rainfall in one day), an 168 association was formed to bring together the grape growers of the Mercurey appellation with the 169 objective of coordinating soil conservation and flood mitigation efforts. This association had two main 170 goals: (1) to simplify the parcel pattern geometry, and (2) to take advantage of these simplifications to 171 develop a network of hydraulic structures to collect and trap sediments. Three types of structures were 172 built (Figs. 2 and 3) (Fressard and Cossart, 2019). First, on the upper slopes, a network of hedges and 173 counter-slope paths were used to hamper the hydro-sedimentary flow between the plots and the 174 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.

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- **3. Methods**
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3.1. SUM measurements

185 **3.1.1.** General principle

186 The Stock Unearthing Method (SUM) developed by Brenot et al. (2006; 2008) has been widely used to 187 estimate soil erosion in European vineyards (Brenot et al., 2008; Casalí et al., 2009; Paroissien et al., 188 2010a; Rodrigo-Comino et al., 2016, 2018a, 2018b). This method is based on the unearthing of the vine 189 stock from the graft union, which is presumed to be spatially immobile in three dimensions. The graft 190 union is thus considered a passive marker of soil erosion. Since the Phylloxera crisis in the 19th century, 191 most European vines are grafted onto American stocks (underground roots), which are the only grape 192 variety able to resist the pest. For agronomic reasons, the graft union point is systematically placed 1 193 or 2 cm above the ground when planting young vines. This a priori initial height is variable depending 194 on bibliographical sources (e.g. 1 cm for Brenot et al., 2008 and 2 cm for Paroissien et al., 2010 and 195 Rodrigo-Comino et al., 2018). The absolute position of this point is affected by a limited downwards 196 shifting through time (Reynier, 2011) that has been quantified to be 0.2 mm.yr⁻¹ by Brenot et al. (2008) 197 for pinot noir varietal (varietal grown in Mercurey). Measurement of the distance between the graft 198 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 dynamicsto 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.

204 3

3.1.2. ISUM corrections

205 The ISUM method (Rodrigo-Comino and Cerdà, 2018) involves the acquisition of measurements in the 206 interrows, which are known to be more affected by erosion and tractor compaction. Additionally, the 207 practice of ridging and un-ridging the vine rows is frequent in viticulture, and tends to artificially reduce 208 the gap between the graft union and the ground on the vine row, whereas the interrow is artificially 209 deepened. Measurements are conducted along a string stretched between two vine plants graft unions 210 (or at a specific distance from the graft union on the plant) located on either side of the interrow (Fig. 211 4). This technique is very similar to that using erosion pin meters, which are widely used to measure 212 soil roughness or to map gully erosion volumes (e.g. Casalí et al., 2006). Further details on the practical 213 application of ISUM are provided in section 3.1.3.



214

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

216 Comino and Cerdà, 2018).

3.1.3. Field measurements and sampling strategy

218 We used the classical SUM method to measure 2359 vine plants over seven plots in the sub-catchment 219 of Monthelon (plots referred to as A–G; Fig. 5), which consists in manually measuring with a ruler the 220 distance between the graft union and the soil (given in cm with a 0.5 cm accuracy as suggested by 221 Brenot et al., 2008). To minimize the errors that can arise from soil roughness (effect of tillage and 222 stoniness), measurements were performed systematically on the downhill side of stocks and 223 conducted in winter (as suggested by Brenot et al., 2008 and Paroissien et al., 2010). The main 224 objective was to estimate the erosion rates on different types of parcels representing the diversity of 225 the topographic characteristics of the area (steep to long and gentle slopes), as well as the various ages 226 of the vine plants (from 9 to 42 years). In the investigated plots, measurements were made at a 227 sampling distance of every 2 rows and every 3 plants in-row. This returned regular nodes on a griding 228 of 3 x 3 m. The positions of all measured vine stocks were determined by differential GPS with a 229 centimetric x, y, z accuracy. The z values (altitude) were not used for volumetric calculations as the 230 GPS vertical accuracy (centimetric) is beyond what is requested by SUM.

231 To provide maps of the spatial distribution of erosion rates, we performed a spatial interpolation of 232 the measured SUM values. For this, we selected the Topo to Raster function of ArcGIS, as it is often 233 considered to be one of the best methods for working with topographic data (Zheng et al., 2016). The 234 output cell size was set to 1 m, which is in good accordance with the accuracy of the initial data (grids 235 of 3 m), and did not lead to excessive interpolation. Previous studies showed that other interpolation 236 techniques (e.g. IDW, Kriging, EBK, RBFs) might also be suitable for deriving erosion surfaces (Rodrigo-237 Comino et al., 2019), but an accurate evaluation of them was considered beyond this study. Volume 238 calculations (above and beyond the reference level - initial topsoil surface) were performed using the 239 3D analyst extension of ArcGIS to obtain the eroded and accumulated volume for each plot. The values 240 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 241

- area (calculated using standard GIS tools), the age of vine (obtained from vine growers interview), and
- 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.



246 Figure 5: Location of the field investigations conducted

247

3.1.4. Estimation of the error margin

In the SUM method, five main types of error can influence the final soil loss results: (1) imprecision in
the measurement of the space between the graft union and the ground; (2) variability of the distance
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,
o is the standard deviation, and n is the sample size.

265 Considering independence and additivity principles on the error values, the planting error and the 266 measurement error were combined using the quadratic sums of the individual terms.

267
$$e_{total} = \sqrt{e_{planting}^2 + e_{measure}^2}$$

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. 274 Two test rows of vines were measured using the ISUM method. These rows were in two distinct plots 275 characterized by contrasting agricultural practices: the presence or absence of ridging and un-ridging. 276 During the field survey, two distinct types of vine row morphology (V-shaped and flat) were observed, 277 and these were considered to be relevant to the investigation. We therefore conducted ISUM5 278 measurements, which involved three additional points of measurements in the interrow. This resulted 279 in a total of five points: two graft union measurements, one on either side, and three measurements 280 in the interrow spaced at 25 cm, as the interrow length was 1 m. Higher resolution measurements 281 were not considered, as comparative studies showed that a five-point ISUM is a good compromise 282 between accuracy and the time required for field work (Rodrigo-Comino et al., 2019).

283

3.2. Volume estimation in sediment traps

284 The dredging of a sediment trap, a counter dip path, and a storm basin, offered the possibility to 285 measure trapped volumes in four main points of the study area. The volumes were estimated by 286 measuring the length, width, and height of earth mounds, and considering their shape as being 287 pyramidal. The measured volumes were then related to the bulk unit weight, the last dredging date 288 (obtained from the winegrowers association), and the upslope contributing area, to obtain the specific 289 accumulation rate in the sediment collector/path. The values are expressed in t.ha⁻¹.yr⁻¹. We arbitrarily 290 assumed a 10% error margin on the measurements made using this technique, which was added to 291 the variability in the bulk unit weights obtained from laboratory analyses.

292

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 berepresented as:

$$301 L = \left(\frac{\lambda}{22.13}\right)^m$$

302 where λ is the slope length (in meters) and m is equivalent to 0.5 for slopes steeper than 5%, 0.4 for 303 slopes between 3%–4%, 0.3 for slopes between 1%–3% and 0.2 for slopes less than 1%.

304 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 ≥ 0.09
- 307 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).

312

- **4. Results**
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4.1. Methods implementation for erosion assessment

315

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 321 measurement was 0.21 cm. Combining these two error margins returned a mean error of 0.33 cm per

322 vine plant. Therefore, the volume calculations are systematically processed within this range (mean ±





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

On plot B, the mean bulk density was 16.5 KN/m³ (values ranged from 15.6 to 17.2), whereas on plot D it was 15.38 KN/m³ (values ranged from 15.7 to 15.9). The bulk density of the material in the sediment trap was 13.8 KN/m³ (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).

333

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).





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 two cross sections were 10.6 and 17.3 t.ha⁻¹.yr⁻¹ for section A using SUM and ISUM, respectively, and 341 342 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 applied on plots characterized by a flat morphology (no deep incision affecting the interrow). Finally 345 on the basis of these field observations, a 40% ISUM correction factor was applied to results from plot 346 347 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

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

 \pm 2.2 t.ha⁻¹.yr⁻¹, which corresponds to a mean ablation of 0.5 \pm 0.1 mm.yr⁻¹ over a measured timescale 351 352 of 43 years. The mean slope gradient is 6.9°, the slope length is 118 m, LS factor is 3.5 and soil surface 353 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⁻ 354 355 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 356 between 35 to 40%. This plot is characterized by the presence of a small gully (± 30/40 cm deep and 1 357 m wide) on its north side, which significantly increases its mean erosion. It is developed on four vine 358 rows on top, which converge together to form one unique row downslope. With the exclusion of the 359 gully, the plot erosion rate drops to 15.8 ± 3.6 t.ha⁻¹.yr⁻¹, while the gully itself represents a mean erosion 360 rate of 81.1 ± 5.7 t.ha⁻¹.yr⁻¹. Field observations showed that this gully originates from a dysfunction in 361 the sediment collection system. A small local breach in the counter dip path creates an overspill of the 362 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 363 364 slope is 6.6° (the lowest gradient of all the slopes, but close to that of plot A), the length 77 m, LS factor 365 is 2.7 and stoniness is between 30 to 35%. According to information obtained from interviews with the 366 vine growers, this plot was recently backfilled (5 years ago), potentially contributing to its significant 367 aggradation. Moreover, this plot is characterized by the lowest LS factor of the selected plots 368 constituting also a context potentially less favorable to erosion. Plots D and E are affected by severe erosion rates of 43.1 \pm 3.6 t.ha⁻¹.yr⁻¹ (3.5 \pm 0.2 mm.yr⁻¹) and 53 \pm 5.8 t.ha⁻¹.yr⁻¹ (4.7 \pm 0.4 mm.yr⁻¹), 369 370 respectively. These two plots have the highest LS factor (respectively 6.4 and 6.5), have a high stoniness 371 (45 to 50%) and are the youngest measured in this study (15 and 9 years, respectively). The maps show 372 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 100 373 374 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 (0.3 375 376 \pm 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.



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382 Figure 8: Erosion maps of the seven plots investigated

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4.3. Comparison with potential driving factors

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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<sup>-1</sup>.yr<sup>-1</sup>. On the opposite plots D and E exhibit high LS factor (above 6) and
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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).

396 A relationship can be visually deduced between soil surface stoniness and soil erosion rates (even if R² 397 is low: 0.11, fig. 9.E). Plots affected by higher erosion rates are characterized by a higher surface 398 stoniness. This relationship appears counterintuitive since the soil surface stoniness is often 399 considered having a negative effect on sediment yield and thus, can be considered as natural soil-400 surface stabilizer (e.g. Poesen and Ingelmo-Sánchez, 1992). In this case, it can be interpreted as a 401 preferential export of fine sediments by runoff, increasing the coarse material fraction on plots 402 affected by severe erosion. Only plot G can be seen as an exception in this case, which can be explained 403 by the backfilling or by the proximity of the plateau edge which can efficiently feed soil surface with 404 coarse elements.

405 No clear trend can be observed between the soil types and erosion rates as the plots appears unevenly 406 distributed on fig. 9-F. This could be explained by homogeneity of soil types on the study area: both 407 types of soils are Cambic calcic soils, which are only distinguished by the parent material marls and 408 marly-limestone.





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.

4.4. Sub-catchment scale sediment transfer and connectivity

416 In the intermediate counter slope created by a transverse track, the trapped volume of sediments was quantified to be 30 ± 3 m³ for a drained surface of 2.24 ha. These counter slopes are regularly dredged 417 (every 1 to 2 years), depending on their filling rate. We measured the potential erosion over the period 418 419 of a year to be $16.6 \pm 5.9 \text{ t.ha}^{-1}$.yr⁻¹, which is of a comparable order of magnitude to the mean erosion 420 measured on the parcels. On the two sediment traps located downslope of the catchment, the 421 investigations performed by Fressard et al. (2019) allowed evaluation of an erosion rate of 1.31 ± 0.7 422 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 423 affected by construction problems limiting its connectivity to the vine plots and its drainage efficiency. 424 Finally, the sediment export rate measured in a storm basin connected to the main river of the 425 catchment provided a result of 0.13 \pm 0.05 t.ha⁻¹.yr⁻¹, which is much lower than the erosion rates 426 measured on the vine plots, and the sediment traps and counter dip path of the upper slopes.







431 (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).

Plot	Age / timescale	Area	Bulk unit weight	ISUM correcti	Mean slope	Slope length	Surface lowering	Exported	Exported	Soil loss
	(yrs)	(ha)	(KN/m³)	on factor	angle (°)	(m)	(mm.yr-1)	volume (m³)	mass (t.)	(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
В	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
С	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	х	х	х	х	30 ± 3	41.4 ± 14.6	16.6 ± 5.9
S. trap 1	4	17.10	13.8 ± 0.35	x	х	x	x	65 ± 6.5	89.7 ± 31.7	1.31 ± 0.7
S. trap 2	28	16.50	13.8 ± 0.35	x	х	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

439 Table 1: Erosion rates at the plot scale



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

446 **5. Discussion**

447 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 measured the effect of vineyard age on erosion and found a value of 62.5 t.ha⁻¹.yr⁻¹ for young vineyards 459 compared with 3.3 t.ha⁻¹.yr⁻¹ for old ones. A similar pattern was later confirmed by Rodrigo-Comino et 460 461 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 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 466 467 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 (e.g. Govers et al., 1999). Paroissien et al. (2010) measured a mean erosion of 10.5 t.ha⁻¹.yr⁻¹ in 469 470 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.

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5.2. The driving factors of erosion in Mercurey

In the case of Mercurey, it can be stated that runoff plays a significant part in the erosion process, as attested by several rill/gully shapes, fans downslope the plots and a good correlation between erosion rates and USLE-LS factor. The regular (but not systematic) observation of a high degree of stoniness on highly eroded slopes is a supplementary indicator of ongoing sheet wash erosion processes. 479 In addition, the specific practice that consists in backfilling eroded plots with collected soils should be 480 accounted for in the sediment budget to explain the variations of erosion rates regarding the age of 481 vines. This practice reveals a cyclicity in ground elevation variability within vine parcels, as documented 482 by local vine growers. Three steps may be exhibited. First, terraced and deeply-tilled soils combined 483 with low vegetation cover (young plants) are more sensitive to splash and runoff. In addition, tractor 484 compaction is potentially very efficient on these still uncompacted soils: compaction rates (based on 485 bulk density) ranging from 10% to 20% are often observed in various physical and anthropogenic 486 settings (van Dijck and van Asch, 2002 ; Elaoud and Chehaibi, 2011 ; Botta et al., 2012). Although it 487 remains difficult to assess the respective parts of erosion and compaction using the SUM/ISUM 488 method, a rapid increase in the distance between the graft union and the soil is clear over the first 489 years after plantation, and its measurement therefore integrates both processes. Local vine growers 490 estimate that the stage of compaction generally lasts for 3 to 5 years (Fig. 12). After a period of 10 to 491 15 years, the plots show a significant decrease in erosion rate. A progressive reduction of soil erodibility 492 does indeed occur in relation to soil compaction and progressive armoring of soils: erodible loamy soil 493 particles are progressively exported and their stocks become exhausted. Then, soil surface stoniness 494 increases.

495 Consequently, anthropogenic backfilling is performed. In Burgundy, vine-growers apply this strategy 496 every 15 to 20 years, depending on the local situation. In the case of extreme morphogenic hydro-497 meteorological events, backfilling may occur more frequently. The objective of backfilling is to 498 compensate for soil losses by adding an external supply of soil, providing earth material to cover the 499 graft-union. Therefore, in old vineyards, the measured erosion rates (considering the time elapsed 500 since plantation) may reveal an apparent equilibrium. The results obtained on the oldest vineyards in 501 Mercurey (plots A and G) do indeed show that the erosion rates stabilized at between roughly 4.5 to 502 10 t.ha⁻¹.yr⁻¹ over long time periods (many decades). However, these values remain much higher than 503 the estimated tolerable erosion rates for sustainable development of agriculture (Verheijen et al., 504 2009).



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

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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.

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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 overall order of magnitude of the intensity of erosion, even if lower erosion rates are affected by more 525

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.





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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/m³). 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.

549 The ISUM correction factor, which was first applied to Spanish vineyards by Rodrigo-Comino and Cerdà 550 (2018), was shown to be of relevance to our case study. However, the diversity of the interrow 551 morphologies also demonstrates that this technique should be applied with caution, and the 552 correction factor was differently applied according to the interrow morphology and field expertise. In 553 this case study, the ISUM correction value for three plots was 40%, which is much higher than the 554 25.7% proposed by Rodrigo-Comino and Cerdà (2018) for Spanish vineyards. However, four plots were 555 characterized by a correction factor of 0%. This approach is more accurate than the traditional SUM 556 method, but extents the data acquisition time in the field (between 1.5 to 2 times longer on the basis 557 of our experience). Therefore, it remains more difficult to deploy the ISUM method over large areas. 558 Our estimate of the ISUM correction factor is, in this case study, only based on two rows. A larger 559 application of the comparison and also higher resolution measurements in the interrow might help 560 increase the accuracy of the correction factor, which may vary from plot to plot, even on the same 561 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.

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

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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 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 578 579 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 \pm 5.9 in the most upstream counter dip path to 0.13 \pm 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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600 **7. Acknowledgments**

We thank the winemakers association of Mercurey, especially Mr. Duvernay and Mr. Menand, for their interest in our research and for sharing their practical field knowledge in constructive discussions. We are grateful to the trainees Antoine Potot, Clément Alami, and Guillaume Brun for their help during field surveys. This research was funded by the CNRS PEPS-INEE project DES-MES.

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