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Soil degradation caused by a high-intensity rainfall event: Implications for medium-term soil sustainability in Burgundian vineyards

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Abstract

The purpose of this paper is to provide a sediment-flux quantification in a vineyard context (Vosne-Romanée, Burgundy, France) where medium-term soil budget and sustainability are controlled by complex interactions between natural processes (rill erosion) and anthropogenic processes (earth supply transferred back into the rills by the winegrowers).

Concentrated overland flows during the rainfall event resulted in the incision of 13 major rills in the inter-rows, carrying a sediment volume of about 4.77 m^3. Most of the rills were rectilinear and displayed a U shape with strong vertical walls. Rill incision began about 30 m from the upper plot boundary. In the buffer zone located at the lower border of the plot, seven fan systems developed from the material originating in one or two contributory rows. Accumulated volume is estimated at 1.6 m^3. Data from grain-size distribution, and rill and fan volumes, show that erosion is dominated by rilling (70% of the sediment yield) over sheet process (30% of the sediment yield). The net exported soil loss, corresponding to the balance between natural soil loss and anthropogenic supply, ranges between 24 ± 3 t ha^{-1} and 48 t ha^{-1}, over the plot during one hydrologic event. Analyses of the grain-size distribution in the reference soil sample and in the fans reveal that size selectivity has occurred, with preferential export of the fine material (<63 µm) out of the plot, and preservation of the coarsest fractions (>2 mm) in the fans. To evaluate the relative importance in grain-size distribution of natural processes (material loss) over anthropogenic processes (rill-filling by winegrowers), we simulated the temporal evolution of grain-size distribution in surface soil during five successive rainfall events. Our results clearly show that more than 30% of fine material in surface soil was lost in these few events, despite anthropogenic rill filling. This fine-fraction removal may have considerable impact on vineyard sustainability.

Keywords: Sediment-flux quantification; Rainfall event; Hillslopes; Soil sustainability; Vineyards

1. Introduction

Erosion resulting from overland and concentrated overland flows during high-intensity rainfall events is recognised as a major problem for sustainable agriculture. Incision of rills through which sediments are exported has direct consequences on soil conservation, not only in terms of quantity since soil surface is removed, but also in quality since soil fertility is affected because of nutrient loss. Irreversible soil degradation may cause major environmental, economic and social impact damage (Fournier, 1972; Joy, 1982; Haff, 2000; Le Bissonnais et al., 2002), thus making it essential to quantify and predict current soil degradation in order to improve soil management, and soil conservation planning (Wischmeier and Smith, 1978; Goudie, 2005; Morgan, 2005). A detailed understanding of soil erosion across different types of anthropogenic-influenced landscapes is critical for the development of sustainable management practices.

Soil degradation in vineyards is an extremely favourable context for soil loss in comparison with other agricultural lands (Kosmas et al., 1997; Le Bissonnais et al., 2002; Brenot et al., 2006; Hooke, 2006). In vineyards, at medium term (a few years to centennial time scale), soil budget and sustainability are

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controlled by complex interactions and feedback between natural and anthropogenic processes (Vogt, 1970). Natural processes, *e.g.* rill erosion, landslides, mudflows and flooding, contribute to the physical ablation of hillslopes by rilling, and by exporting sediments at the outlet. Much work has been dedicated to the study of natural processes, not only for the assessment of erosion rates in various agricultural contexts (Kosmas et al., 1997), either short term (for a single rainfall event, *i.e.* a few hours, to several rainfall events, *i.e.* a few years), or long-term (for centennial to millennial time scales), but also to characterise rill morphology, (Wicherek, 1991; Wainwright, 1996; Kosmas et al., 1997; Schaller and Emde, 2000; Martinez-Casasnovas et al., 2002; Ramos and Martinez-Casasnovas, 2004). Yet most of the time, in order to maintain soils on hillslopes, erosion effects are counterbalanced by anthropogenic earth supply, stored in plot toe. Rills which develop during rainstorms are filled by the earth that was eroded, deposited at the footslope, and transferred back into the rills by the winegrowers (Fig. 1). However this earth cycle is biased since part of the sediment is probably exported. Therefore there is a need to quantify the relative importance of natural and anthropogenic processes, to lead to further discussion of the sustainability of agricultural soils.

In this paper, we describe the results of a detailed field survey, carried out after a yearly return high-intensity rainfall event in the Vosne-Romanée vineyards (Burgundy, France). We quantify patterns and rates of soil erosion in the field to evaluate short-term soil degradation and its impact on medium-term soil modifications, *i.e.* volumes and textures, in Burgundian vineyards, where intensive erosion phenomena represent a critical situation for soil preservation.

2. Data and method

2.1. Study area

The selected site is located on the hillslopes of Vosne-Romanée vineyards, in the « Côtes de Nuits » area (Burgundy, France), where frequent high-intensity rainfall events occur annually (Fig. 2). Wine-growing developed here on a fault-scarp relief in the Middle Ages (Dion, 1959). These historical hillslopes, induced by the Bressan rifting, form the eastern border of the Burgundy plateau. The hillslopes develop on Middle to Upper Jurassic limestones and marls, and are covered by colluvium soils of argillaceous-gravelly nature and formed by Weichselian cryoclastic deposits ("grèzes litées") reaching up to 3 m thick (Journaux, 1976). Soils were described following the method of Baize and Girard (1995). These deposits are draining, non-cohesive, easily erodible and display a low organic content (<1%) like all vineyard soils in Côte-d'Or (Mériaux et al., 1981). Measured dry soil bulk density of the soil top layer varies between 1.25 and 1.5 t m-3. The texture is rather homogenous over the whole plot and is composed of 40% of clays and silts, 50% of gravels (2 mm to 10 mm) and a low sand and boulder content. The topsoil are ploughed (Mériaux et al., 1981). The argillaceous aggregates with polyhedral blunted to grained form are slightly structured. No pedogenetic segregation has been observed.

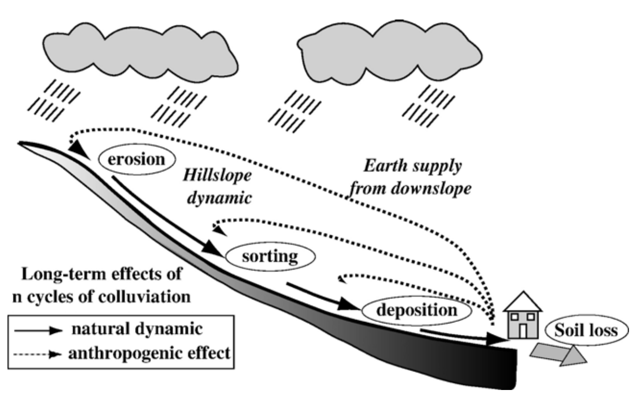

Fig. 1. Hillslope dynamics resulting from the interaction between natural and anthropogenic processes in a vineyard context.

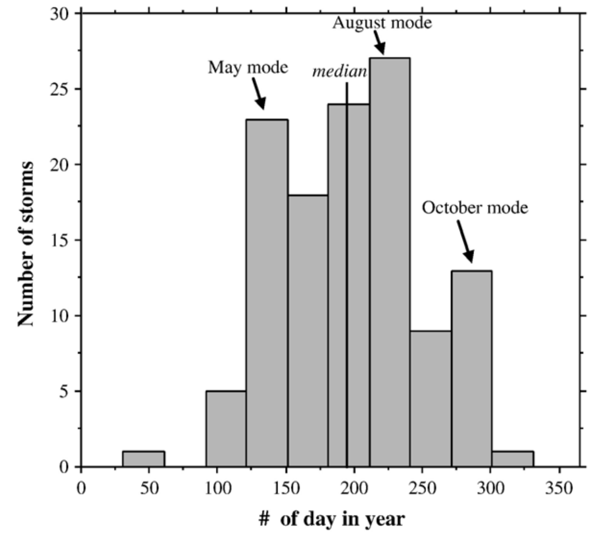

Fig. 2. High-intensity rainfall events recorded between 1992 and 2001 in the Vosne-Romanée vineyards.

The landscape is characterised by a vine monoculture where the parcellar limits, *i.e.* paths and walls, have formed the only discontinuities along the hillslopes since mechanisation in the middle of the 20th century (Garrier, 1989). The morphological and soil characteristics of this plot, the agricultural practices in use, and the patterns of soil erosion and distribution observed here make this site an ideal example for the study of soil degradation in Burgundian vineyards.

2.2. Plot characteristics and agricultural practices

The study site (47.1615°N, 4.945°E) is a 4300 m^2 plot in the Vosne-Romanée vineyards, 126 m long and 35 m wide, located on the upper part of the hillslope. We made a high-resolution digital elevation model (DEM) from differential TRIMBLE®GPS measurements (cm resolution). The plot is characterised by a slightly convex morphology and a slope increasing from 10° to 12°. The elevation decreases from

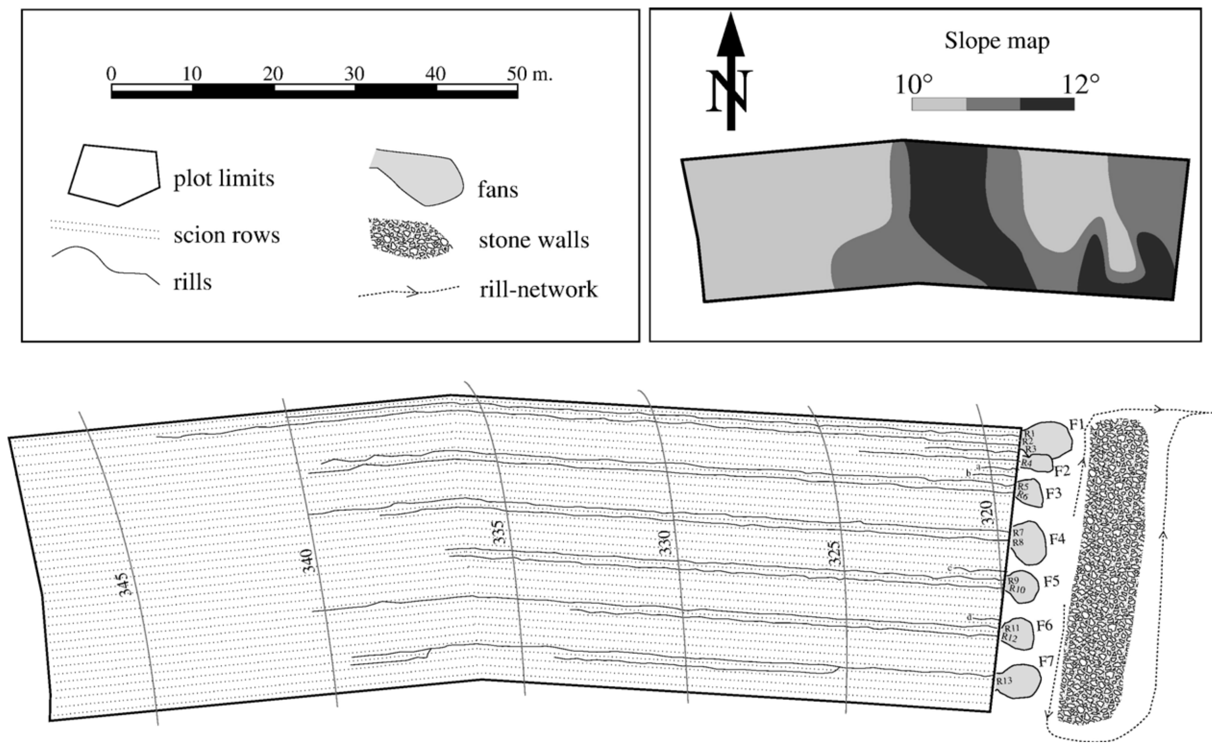

Fig. 3. Slope and plot map showing the regularly spaced rills and the associated fans. The major rills are numbered from 1 to 13, the fans from 1 to7.

347 m upslope, to 319 m downslope. Inter-rows display a mean length of 122 m.

The lower border of the plot consists of a 5 m-wide horizontal path, causing deposition and acting as a buffer zone during storm events (Fig. 3). The vine stocks are planted parallel to the slope providing propitious conditions for rill initiation and formation. Non-grassed inter-rows, slope-oriented rows and superficial tilling, once or twice a year, are the most frequent agricultural practices in all Burgundian vineyards, and also in the plot selected for this study. This plot is weeded chemically every five rows by straddle-tractor.

2.3. Rainfall characteristics on 11 June 2004

The mean annual precipitation of the Côtes de Nuits ranges between 700 and 900 mm/yr (Météo-France, 1994). Precipitation distribution is very regular throughout the year, and ranges between 40 et 80 mm per month. From 1991 to 2002, the most rainy months are November and September (respectively 89 and 91 mm per month) while March and August correspond to the least rainy months (41 and 50 mm). The pluviometry of the other months varies between 56 and 79 mm. However, a strong seasonal contrast in rainfall characteristics is observed. During the period from May to October, the Vosne-Romanée vineyards are particularly affected by high-intensity storm events of relatively short duration, whereas the winter season is characterised by frequent low-intensity rainfall events. Between November and April, 52% of rainfall events display an intensity of less than 2 mm/h, 96% are lower than 10 mm/h. In contrast, 68% of the storm activity occurs during the period from 23 May to 6 September. Three periods of storm activity can be individualised: the first ranges throughout May, the second throughout August, and the third occurs between the 27 September–27 October. The second period, *i.e.* the summer months, corresponds to the highest risk period for soil erosion because of the occurrence of high-intensity rainfall events (Fig. 2). From 1991 to 2002, 120 storm events were recorded, with 10 events displaying a total precipitation ranging between 30 mm and 50 mm and with the strongest event reaching 63 mm (data from Romanée-Conti Domain data collection, Table 1). Among these, one important event, characterised by 40 mm of

Table 1
Rainstorm frequency in the Vosne-Romanée vineyards over 1992–2001

Storms [1991–2002]	
Number of days	4383
Number of storm events (days)	120
Frequency (% days)	2.7
Frequency (per year)	10.0

Table 2
Rainstorm frequency in the Vosne-Romanée vineyards according to their daily intensities

Storm event range (mm/day)	Number of events	Frequency (per year)
>60	1	0.1
]50–60]	0	0.0
]40–50]	1	0.1
]30–40]	9	0.8
]20–30]	17	1.4
]10–20]	29	2.4
]0–10]	63	5.3

Fig. 4. A linear erosive structure displaying a U-shape morphology with steep walls.

precipitation in 2 h, and representative of a roughly yearly return periodic event, was recorded on 11 June 2004 (Table 2).

Field observations show that events characterised by rainfall intensity lower than 20 mm h^{-1} are slightly erosive. Therefore a high percentage of annual soil loss is represented by the soil loss occurring during rainfall events like that of 11 June 2004.

2.4. Description of rills, fans and sediments

Concentrated overland flows occurring during the 2 h of rainfall resulted in the formation of a rill network in the inter-rows. Part of the sediment was deposited in the buffer area (fan systems) while the rest was exported out of the system (Fig. 3). In order to quantify the volume of sediment eroded, preserved and exported just after the rainfall event, we measured: (1) the morphology and volume of the erosion structures, *i.e.* the rills, (2) the morphology and volume of the depositional structures, *e.g.* the fans and (3) the grain-size distribution.

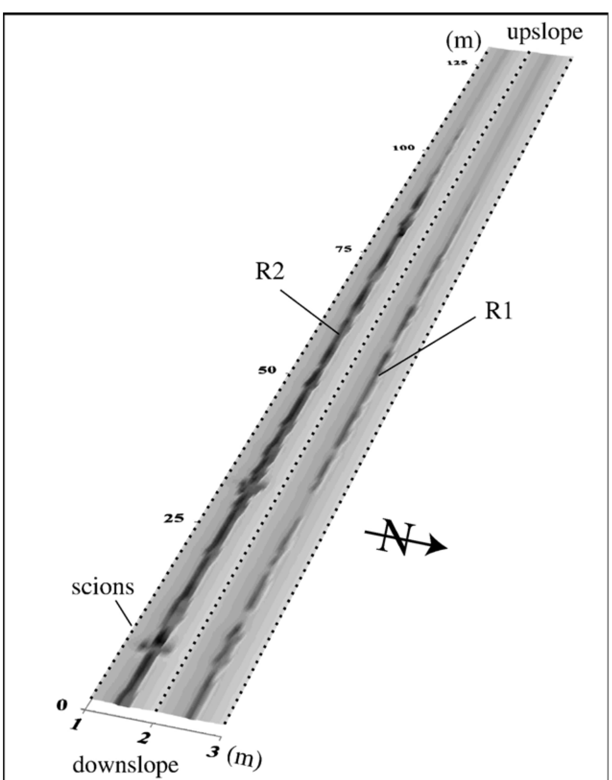

Fig. 5. Digital reconstruction of the R1 and R2 rill system, used to assess rill volume.

Table 3
Description of length and volume of the 13 major rills, and volume of their associated fans

Rill	Row length (m)	Rill length (m)	Rill volume (m3)	Total (m3)	Fan	Fan volume (m3)
R1	125	91	0.34	1.51	F1	0.40±0.06
R2	125	106	1.17			
R3	124	10	0.02	0.06	F2	0.08±0.03
R4	124	20	0.04			
R5	123	87	0.32	0.72	F3	0.05±0.02
R6	122	87	0.40			
R7	122	87	0.44	0.93	F4	0.48±0.08
R8	122	77	0.49			
R9	121	70	0.20	0.37	F5	0.14±0.04
R10	120	70	0.17			
R11	118	87	0.41	0.62	F6	0.1±0.03
R12	118	53	0.21			
R13	116	82	0.56	0.56	F7	0.28±0.07
Total	1580	927	–	4.77		1.6±0.3

The error margins in the fan volume estimations are related to measurement errors in the field.

2.4.1. Rill description

After the rainfall event, 13 long major rills (numbered 1 to 13) and 4 very short minor rills (a to d) were identified in the inter-rows (Fig. 3). Most rills were rectilinear, parallel to the maximum slope, and displayed a U shape with steep vertical walls (Figs. 4 and 5). The morphological parameters of rill

Table 4
Width, depth, width/depth ratio and cross-section values of major rills

	Width (cm)		Depth (cm)		Width–depth ratio		Cross-section area (m^2)	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
R1	9.01	3.64	4.37	1.36	2.16	0.97	0.0037	0.0025
R2	14.21	6.95	7.50	2.92	2.17	1.44	0.0110	0.0063
R7	11.07	3.74	4.37	1.72	2.80	1.80	0.0052	0.0027
R8	12.85	4.05	5.04	1.64	2.82	1.34	0.0065	0.0029
R9	8.42	4.53	3.29	1.31	2.99	1.81	0.0027	0.0015
R10	7.61	2.08	4.10	1.67	2.14	0.85	0.0032	0.0017
R11	12.92	5.33	4.14	1.60	3.54	1.96	0.0013	0.0005
R12	11.16	3.38	3.74	1.56	3.43	1.77	0.0043	0.0025
R13	10.91	2.37	4.57	1.29	2.76	0.56	0.0047	0.0017

Table 5
Morphological characteristics of minor rills

Rill	Row length (m)	Rill length (m)	Eroded volume (m^3)
a	123	5	0.009
b	123	5	0.009
c	121	8	0.0085
d	119	4	0.008

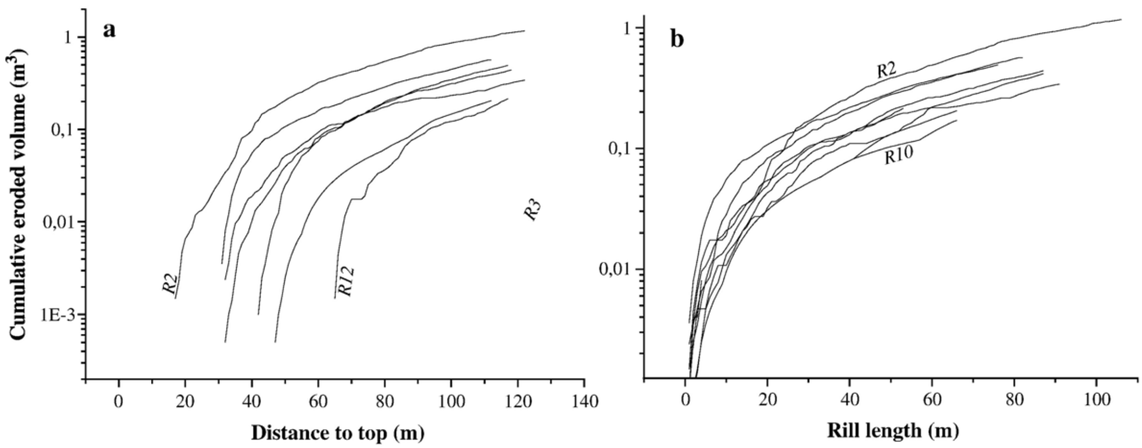

Fig. 6. a: Relationship between cumulative eroded volume and rill length. b: Relationship between cumulative eroded volume and distance from upper plot boundary.

incision (length, depth, and width) were measured at 1 m resolution in the field, for all rows where a rill appeared, over a surface of 1580 m2. Rills occurred over 59% of the row area (Fig. 3). Results of all these measurements are reported in Tables 3 and 4 for the major rills, and Table 5 for the minor rills. Rills, as illustrated in Fig. 3, are not randomly-distributed spatially. They form in two contiguous rows, recurrently every five rows, and this uniformly at plot scale. Their length varies from 10 m to 106 m, with most ranging between 70 and 90 m (Table 3, Fig. 6). Most width/depth ratios range between 2.14 and 3.43 (Table 4), suggesting that these rills display the most hydraulically efficient shapes for conveying water flows (Moore and Burch, 1986). These rills behave like ephemeral rills: indeed, despite tillage and filling operations which erase ephemeral marks on the surface, these rills develop along the same path over several years, showing temporal and spatial persistency in location. However, although some studies define incisions higher than 10 cm as ephemeral rills (Martinez-Casasnovas et al., 2002), we prefer to attribute these erosion structures morphologically to rill structures, as their specific cross-section never exceeds 0.093 m^2, in accordance with the classification of Poesen et al. (2003).

Rill volumes were processed with the aid of Surfer®, using a Kriging method (Fig. 5). Volumes range from 0.17 m^3 to a maximum of 1.2 m^3 (in inter-row R2), most ranging between 0.3 and 0.5 m^3 (Table 3). The total exported volume is estimated at 4.77 m^3. For most rills, the upper slope domain was devoid of linear erosion structures because overland flow had not yet been concentrated. Incision was noted to begin about 30 m from the upper plot boundary, and progressed incising downslope non-linearly. Since all the rills behave similarly (Fig. 6), we propose the following empirical law relating the eroded volume of each rill to its length L:

$$\log(V_{\text{eroded}}) = 0.019{*}L - 2.05$$

using a relationship with an r^2 coefficient of 0.96. Fig. 7, which presents the cumulative eroded volume relatively to the upslope distance, shows that rill volume varies as a function of rill length.

2.4.2. Fan description

During the rainfall event, a topographically induced deposition occurred in the buffer zone, forming seven fan

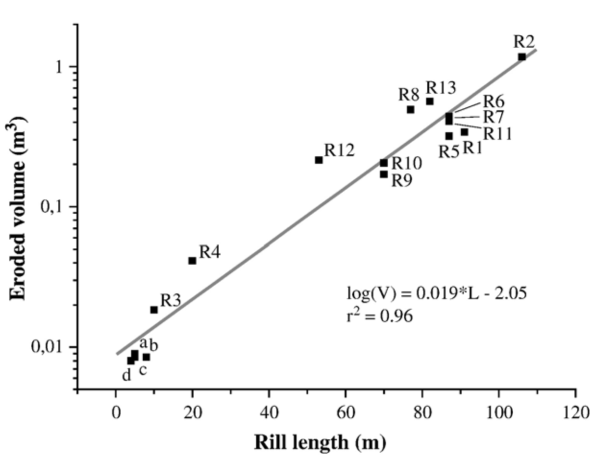

Fig. 7. Relationship between eroded volume and rill length.

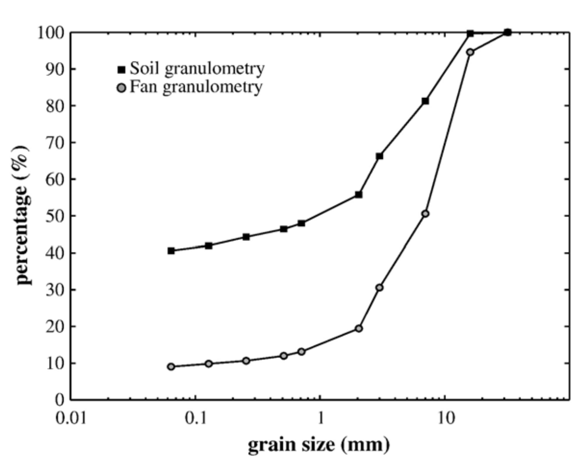

Fig. 8. Grain-size distribution in reference soil sample and in fan.

Table 6
Estimation of rill/inter-rill contribution from a mass balance performed in rill system 7+8 and associated fan F4

Grain size (mm)	Rills R7+R8 ($0.93\ m^3$)		Fan F4 ($\sim 0.5\ m^3$)		Inter-rill (kg)		Rill+ inter-rill
	%	kg	%	kg	%	kg	kg
>7	18.73	217.8	49.4	308.8	18.73	91.0	308.8
>3	15.00	174.4	20	125	15.00	72.8	247.2
>2	10.47	121.7	11.15	69.7	10.47	50.8	172.5
>0.71	7.80	90.7	6.3	39.4	7.80	37.9	128.6
>0.5	1.60	18.6	1.15	7.2	1.60	7.8	26.4
>0.25	2.13	24.8	1.35	8.4	2.13	10.4	35.2
>0.125	2.33	27.1	0.8	5	2.33	11.3	38.5
>0.063	1.33	15.5	0.8	5	1.33	6.5	22.0
<0.063	40.60	472.0	9.05	56.56	40.60	197.2	669.1
Total soil loss (kg)		1162.5		625		485.6	1648.1

systems. Fig. 3 shows that fans developed from material eroded from one or two contributory rows. Their maximal length, width and thickness display variable dimensions, from 1 to 5 m wide, from 1 to 5 m long, and from 15 to 25 cm thick. Fan volume was calculated assuming a conical morphology. Obtained fan volumes vary from 0.1 to 0.47 m^3, with a total cumulated volume of 1.6 m^3 (Table 3). Traces of flows over fan surfaces suggest that part of the sediment has been exported out of the plot (Fig. 3).

2.4.3. Grain-size distribution

Sediment boxes were placed at the end of rows to collect eroded material in order to define the grain-size distribution of the eroded sediments in the rills, and that of the preserved sediments in the fans. Samples were compared to a reference bulk soil sample collected in the 0–20 cm soil layer before the rainfall event. Grain-size distributions were obtained by sieving on undispersed material to give information on size selectivity. Observations of grain-size distribution in the reference sample and in the boxes reveal that a wide range of grain sizes was transported during the flow. We therefore assume that the differences in percentage in eroded and deposited sediments are not representative of selective detachment, but result from size selection during sediment transport and deposition.

Analyses of grain-size distribution in the reference soil sample show that the soil was mainly composed of a loamy–clay fraction (~40%) and of gravel pebbles (~45%) before the rainfall event (Fig. 8). Sandy fractions were present in moderate quantity (<20%). There is little variation in the percentage of sandy fractions between the reference sample and the fans. Grain-size distribution in the fan differs mainly by the higher percentage of the coarsest fraction (>2 mm) and the lower percentage of the loamy–clay fraction, which only represents 10% of the observed grain sizes (Fig. 8). This suggests that size selectivity has occurred, with preferential export of fine material (<63 μm) out of the plot, and preservation of the coarsest fractions (>2 mm) in the fans.

3. Results: soil loss, net exportation, soil ablation and evaluation of the contribution of rill/inter-rill

We estimated total soil loss, soil ablation, net exportation, *i.e.* the balance between soil loss and anthropogenic supply, and rill/inter-rill contribution from a dataset of grain-size distribution and rill and fan volumes.

As all rill and fan systems behave very similarly over the plot, we evaluate the rill/inter-rill contribution from mass balance performed on rill systems 7+8 and associated fan F4 (Table 6). We estimated independently the amount of sediment transferred through the rill and that preserved in the fans, from the volume dataset and from grain-size distribution, for each grain-size class and for a bulk density of 1.25 (Table 6). A mass excess of 91 kg of coarsest fractions preserved in the fan compared to the amount of sediment eroded by the rill was found, suggesting that inter-rill erosion must have occurred (Table 6). The mass of the coarsest fraction eroded in the inter-rill is obtained by subtracting the mass preserved in the fan from that eroded in the rill, assuming that all coarsest fractions were preserved, which is supported by the fan and rill grain-size distributions. Based on this estimation and on the reference soil grain-size distribution, and assuming that inter-rill erosion occurred by removing a thin layer uniformly, it becomes possible to evaluate the total amount of sediment eroded in the inter-rill (486 kg) and the amount of sediment eroded for each grain class. Finally, we estimate a total sediment yield of 1.6 t for this system, with rills representing 70% of the soil loss, twice as high as inter-rill erosion (Table 6). We therefore suggest that the larger rills not only act as an efficient way to export sediments, but also as sediment sources.

Table 7
Quantification of soil loss and net exported soil for each rill and its associated fan

Rill	Rill volume (m^3)	Rill area (m^2)	Row area (m^2)	Eroded height (mm)	Fan	Fan volume (m^3)	Net exported volume (m^3)	Net soil ablation (mm)
R1+R2	1.51	197	250	6.8±0.8	F1	0.40±0.6	1.11±0.6	4.4±0.2
R3+R4	0.06	30	248	1.1±0.9	F2	0.08±0.03	0	0±0.1
R5+R6	0.72	174	245	3.5±0.6	F3	0.05±0.02	0.67±0.02	2.7±0.6
R7+R8	0.93	164	244	4.7±0.9	F4	0.48±0.08	0.45±0.08	1.9±0.3
R9+R10	0.37	140	241	2.1±0.6	F5	0.14±0.04	0.23±0.04	0.9±0.1
R11+R12	0.62	140	236	3.5±0.9	F6	0.1±0.03	0.52±0.03	2.2±0.1
R13	0.56	82	116	5.8±1	F7	0.35±0.07	0.358±0.07	1.8±0.6
Total	4.77	927	1580	4.1±1		1.6±0.3	3.17±0.3	2±0.2

The soil ablation values are estimated when considering the entire rill area or the row area. The error margins in the fan volume estimations are related to measurement errors in the field. The error margins in the net exported volume estimations are induced by the error margins in the fan volume estimations. Net soil ablation estimations are obtained by dividing the net exported volume by the row area. The error margins in the net soil ablation values are related to the error margins in the fan volume estimations.

Table 8
Sediment budget at the plot and area scales (a) when considering only rill erosion, and (b) when considering rill + inter-rill erosion

(a)

Row area (m^2)	Rill volume (m^3)	Eroded mass (t)	Fan volume (m3)	Accumulated mass (t)	Rill - fan volume (m^3)	Rill-fan Mass (t)	Net soil loss rate (t/ha)	Soil ablation by rill erosion (mm)
1580	4.77	6	1.6±0.3	2±0.3	3.17±0.3	3.9±0.3	24±3	2±0.2

(b)

Row area (m^2)	Total soil loss volume (m^3)	Eroded mass (t)	Fan volume (m3)	Accumulated mass (t)	Net exported volume (m^3)	Eroded Mass (t)	Net soil loss rate (t/ha)	Total soil ablation (mm)	Total soil ablation at plot scale (mm)
1580	7.8	9.75	1.6±0.3	2±0.3	6.2±0.3	7.7±0.4	48±0.3	3.9	1.4

We further established a sediment budget at the plot and row area scales. We call plot soil loss the volume of sediment exported through the plot, *i.e.* through the rill and inter-rill area. The net exported volume at the outlet boundary can be derived by subtracting the volume of sediment trapped in the fans, which is used by winegrowers to fill the rills, from the soil loss. Visualisation of the network shows that all rills contribute to soil loss. By taking all row data into account, we assess at 4.77 m^3 the volume of sediment eroded by this event through the rill systems, which corresponds to a mean soil loss of 6 t, taking a bulk density of 1.25 (Table 6; Table 7). Mean soil ablation induced by rill erosion is obtained by dividing the total volume of the rill (4.77 m^3) by the surface area of the row (1580 m^2), and corresponds to a mean topographic lowering of 4.1 mm in one event (Table 7; Table 8). By taking the 30% additional inter-rill erosion into account and assuming that all rills behave similarly, soil loss is estimated at 7.8 m^3 for this event, a net soil loss rate of 48 t/ha per event, a mean soil ablation of 3.9 mm at the row area scale (surface area 1580 m^2), and a mean soil ablation of 1.4 mm at the plot scale (surface area 4300 m^2).

For rill erosion alone or rill plus inter-rill erosion, net exported volume is estimated respectively as 3.17 m^3 and

Table 9
Compilation of erosion rates in different vineyard contexts

Location	Time scale (yr)	Mean soil loss (t/ha)		References
		day^{-1}	yr^{-1}	
Albugnano, Italy	<1	>70.18		Tropeano (1983)
Mongardino, Italy			32.55	Tropeano (1983)
Santa Victoria d'Alba, Italy			0.32	Tropeano (1983) in Hooke, 2006
Santa Victoria d'Alba, Italy			0.78	Tropeano (1983) in Hooke, 2006
Santa Victoria d'Alba, Italy			2.73	Tropeano (1983) in Hooke, 2006
Alsace, France	>5		32	Litzler (1988)
Champagne, France	<1	3.2–4.6		Litzler (1988)
Champagne, France	>1		1.16	Litzler (1988)
Switzerland	>1		15–25	Litzler (1988)
Languedoc, France	40		5.5	Litzler, 1988
Champagne, France	3		1.5	Ballif (1990)
Champagne, France	<1	0.136		Ballif (1990)
Champagne, France	<1	0.8–1.3		Ballif, 1990
Champagne, France	3		0.6	Ballif (1990)
Aisne, France	3		35	Wicherek, 1991
Duro, Portugal	10		0.39	Figueiredo and Ferreira (1993) in Hooke, 2006
Duro, Portugal	10		1.1–2.8	Figueiredo and Ferreira (1993) in Hooke, 2006
Spata, Greece			0.38–2.53	Kosmas (1993) in Hooke, 2006
Var, France			2.8–53.9	Viguier (1993) in Hooke, 2006
Var, France				Viguier (1993) in Hooke, 2006
Roussillon, France		1.4		Kosmas et al. (1997)
Moselle, Germany	<1	52		Schaller and Emde, 2000.
Moselle, Germany	<1	0.2		Schaller and Emde, 2000
Rheingau, Germany	<1	6.2		Schaller and Emde, 2000
Germany	<1	15		Schaller and Emde, 2000
Catalonia, Spain	<1	207		Martinez-Casasnovas et al. (2002)
Vosne-Romanée, France	54		7.6	Brenot et al. (2006)
Aloxe-Corton, France	50		14.9	Brenot et al. (2006)
Monthélie, France	32		13.5	Brenot et al. (2006)
Vosne-Romanée, France	<1	24–48		This study

6.2 m^3, corresponding to about 66% to 89% of total soil loss, and to net soil loss rate ranging between 2 mm and 3.9 mm at the row area scale (surface area 1580 m^2), and a mean soil ablation of 1.4 mm at the plot scale (surface area 4300 m^2) (Table 8a and b). Net soil loss rates during this event range between 24±3 t ha^{-1}. and 48 t ha^{-1} respectively for rill erosion alone or rill plus inter-rill erosion. Values obtained are high, but consistent with rates calculated in vineyard contexts (Table 9, see Kosmas et al., 1997; Martinez-Casasnovas et al., 2002 and Hooke, 2006, for a review): 47–70 t ha^{-1} yr^{-1} in NW Italy (Tropeano, 1983), 35 t ha^{-1} yr^{-1} in the mid-Aisne region (Wicherek, 1991), 22 t ha^{-1} yr^{-1} in the Penedès-Anoia region (NE Spain) (Usòn, 1998), 34 t ha^{-1} yr^{-1} during an extreme event (Wainwright, 1996). These high rates are also consistent with other studies showing that ephemeral gully/rill systems are major contributors to sediment production in agricultural lands (10 to 90% for Govers and Poesen et al., 1988; 70–80% for Boardman, 1996; 44–83% for Martinez-Casasnovas et al., 2005).

4. Discussion

Quantification of erosion occurring during high-intensity rainfall shows that Burgundy vineyard soils are affected by high erosion rates. Assessed soil-loss rates, estimated at more than 24±3 t ha^{-1} in one event highlight the existence of an anthropogenic-related disequilibrium of the slope dynamics in these vineyards, if compared with mean soil production rates, ranging from 0.01 to 0.1 t ha^{-1} yr^{-1} (Heimsath et al., 1999; Minasmy and McBratney, 1999). This section discusses anthropogenic-induced soil degradation at short and medium term.

In the short term, this example shows that the erosion rate is enhanced by tillage effects (Fig. 3). Evidence of this anthropogenic influence is exemplified by the very regular rill spacing observed in this plot, which is directly related to the passage of agricultural machinery. The repeated passages, by decreasing soil surface porosity and infiltration, permit the localisation of flow zones, causing an increase in runoff and erosion potential. This interpretation is consistent with other short-term studies showing that the passage of agricultural machinery is responsible for significant modifications in soil properties and in the location of intensively eroded domains (Schaller and Emde, 2000; Van Dijck and van Asch, 2002; Lagacherie et al., 2006).

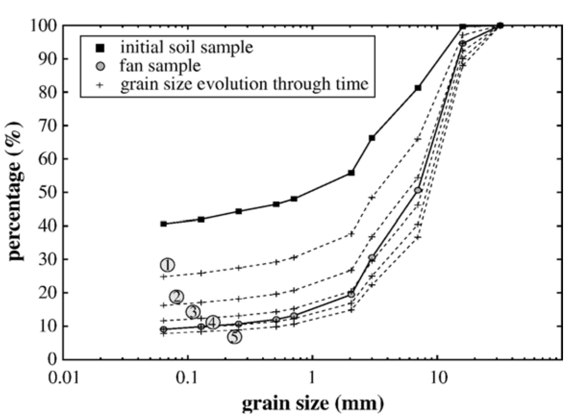

Fig. 9. Simulation showing temporal evolution of grain-size distribution in soil for five successive events.

The effects of short-term erosion on vinestock growth are limited, as long as vine-roots are covered by earth supply. However, medium-term erosion can be more problematic since it provokes a slow but continuous overland soil truncation, despite anthropogenic earth supply. This study shows that assessed soil loss rates exceed soil production rates, and that erosion is selective, since fine materials are preferentially exported out of the plot. To evaluate the relative effect of natural processes (erosion) in comparison to anthropogenic processes (rill-filling by winegrowers) on grain-size distribution and on medium-term soil sustainability, we have written a programme (Matlab©) that simulates the temporal evolution of grain-size distribution in the top soil, for five successive rainfall events (Fig. 9). For this, we assumed that natural soil production rates permit a partial renewal of the top soil between two rainfall events. We also assumed that the top soil and rills are covered after a rainfall event by sediment, depleted in fine fraction, previously stored in the fans and transferred back to the rills by the winegrowers. In this simulation, in order to take into account both natural and anthropogenic effects, grain-size distribution of the top soil is considered to be composed in equal parts of the initial reference grain-size distribution described above, and of a fan grain-size distribution evolving over time. For each event, to calculate this fan grain-size distribution, we consider that the runoff always displays the same characteristics, and acts in such a way that fine-fraction depletion occurs in identical proportions to those observed in the event described above. Although our approach is very simple, the results of our simulation clearly show that repeated rainfall events modify significantly and very rapidly surface soil grain-size distribution (Fig. 9): after only a few events, the top soil has lost more than 30% of its fine material. This removal of the fine fraction may have considerable impact on vineyard sustainability. Indeed, fine particle loss contributes to soil fertility degradation by inducing a depletion of nutrients and organic matter. Winegrowers, now increasingly aware of this problem, experiment different methods at the plot scale, such as inter-row grassing, shortening of rows, and wall reconstruction, which are the primary actions to be generalised to reduce soil loss.

5. Conclusion

The dataset for this plot provides an estimation of the likely soil loss rates in ephemeral gully/rill systems, in a vineyard context, where sediment budget and soil sustainability result from the interactions between natural and anthropogenic processes. Assessed net exported soil loss, the balance between natural soil loss and anthropogenic supply, ranges from 3 m^3 to 6.2 m^3, and corresponds to a mean topographic lowering of 2 to 4 mm at the plot scale. Erosion is dominated by rill (70% of the sediment yield) over sheet erosion (30% of the sediment yield) on these hillslopes. A simple simulation of the temporal evolution of grain-size distribution was performed to document medium-term soil depletion. The results of our simulations show that more than 30% of fine material from the soil surface was lost after only a few events. This fine material is irretrievably lost when exported out of the plot. In the medium term, such depletion may have a major impact on soil fertility degradation and thus on soil sustainability. Such simulations allow the complex links between natural and anthropogenic processes to be explored, thus contributing to a better understanding of dynamic systems in anthropogenic geomorphological contexts, which may help soil scientists to develop soil conservation strategies.

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