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Extreme viticulture:
from a cultural landscape to an economic and environmental sustainability

11-14 May 2022, Vila Real (UTAD)

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Universidade de Trás-os-Montes e Alto Douro (UTAD)
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Seasonality of rainfall erosivity and soil loss extremes and variability in Douro vineyard plots

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Keywords: Soil erosion, Rainfall characteristics, Extreme erosion events, Steep slope vineyards

Abstract. Seasonality and frequency of erosive rainfalls largely affects runoff and soil loss and should drive timing of soil conservation practices and farm operations, an important issue for reducing on-site and off-site erosion impacts in vineyards. This study aims at exploring seasonality and frequency of rainfall erosivity and their relation to the erosional response of vineyard plots located in the Douro Wine Region. Data used in the study are the 10-year records from 5 plots at Quinta de Santa Bárbara, Pinhão (rainfall, runoff, soil loss, vine phenology and tillage operations). EI30 (reference rainfall erosivity index) was computed for different rainfall intensity and height thresholds. IDF curves were derived for durations from 5 min to 24h. Frequency analysis of rainfall height, intensity and erosivity were performed on annual and seasonal basis.Rainfall erosivity is the main factor explaining plots erosional response. From all computed indexes, the best performing was EI30m, calculated with all rains (no threshold), relating at event level in a power function with soil loss (r=0.713). EI30m (796 MJ ha-1 mm h-1 annual average) correlated very well with the original EI30, calculated for events above defined rainfall height threshold (r=0.997). Seasonality affected IDF curves parameters, higher intensity being found in summer than in winter rains for durations shorter than 3 hours. Out of 167, 3 extreme erosion events accounted for ¾ of the total soil loss in 10 years and resulted from rainfalls with return periods from 20 to 100 years. Annual average soil loss has a typical negative exponential relationship with plots vegetation cover. However, plot cover provided by plantation schemes and practices in Douro Wine Region may result insufficient to limit to tolerable rates soil losses triggered by high erosivity rainfalls, using actual vegetation cover management practices alone.

Introduction

Soil erosion is a recognized threat to soil resource in mountain vine-growing regions. Compilations of mean soil loss rates recorded in Mediterranean Europe set vineyards ahead of other land use types. (Rodrigo-Comino, 2018).

Soil surface cover is a key issue for soil conservation in vineyards, as the plot cover fraction by canopies in vine rows is usually smaller than that of the inter-row lanes. Most recommended conservation practices in vineyards are based on herbaceous vegetation management in vine inter-rows (e. g., Biddoccu *et al.,* 2017). However, Figueiredo et al (2021) called the attention for the effect on soil loss rates of plant density, which is decided at vineyard installation and creates the basic structure for erosion control in the vineyard plot.

The different cover layers in a vineyard (vine canopies, plant residues, and herbaceous vegetation) change along the crop year. Their combined contribution to soil protection depends on how cover patterns temporally match rainfalls seasonal distribution (Figueiredo, 2015). Effective erosion control measures should, therefore, focus on critical areas of the vineyard and on critical periods along the crop cycle, where and when cover is insufficient to keep soil loss at tolerable rates (Figueiredo *et al.*, 2020). Furthermore, conservation measures should consider cost-effectiveness for critical design scenarios, as those associated to rainfall variability (Figueiredo *et al.*, 2021). Although scarcely reported, seasonality and frequency of erosive rainfalls is a relevant element of local or regional climates that should drive timing of soil conservation practices and farm operations, so as to reduce erosion impacts in vine-growing regions.

Long-term series of soil loss data are rarely reported in literature (Maertens *et al.*, 2012) and few cases regard vineyard plots (Biddoccu *et al.*, 2017; Figueiredo, 2001). Long data series are essential for understanding soil loss temporal variability, which is primarily determined by variability on rainfall erosivity. Indeed, longer time series may include extreme rainfalls triggering large erosion events, only by chance observed in short term records.

This study aims at exploring seasonality and frequency of rainfall erosivity and their relation to the erosional response of vineyard plots located in the Douro Wine Region.

Methods and sources

The data used in the present study correspond to the 10-year records from 5 plots at Quinta de Santa Bárbara, a State experimental farm that hosted an erosion station, not anymore active, located near Pinhão, Douro Wine Region (41˚10' N, 7˚33' W, 130 m elevation). Records include Rainfall (P), Runoff (R), Soil Loss (SL), vine phenology and farm operations (tillage-based soil management). The plots (32.1 m long by 5.2 m width) were installed in a 45% slope vineyard planted in rows against the contour on a schist derived soil (Dystric Anthrosol), silt loam and with very high rock fragments content and cover (55%). Plots represent edaphic and topographical conditions dominant in Douro vineyards. The plantation scheme, even though not dominant, is commonly found in the region.

Continuous records of rainfall data were treated to characterize rainfalls along the study period from 5 min to annual time intervals. Intensity-duration curves (IDF) were derived from Rainfall Intensity (I) for durations from 5 min to 24h, applying Gumbel distribution on annual and seasonal basis. Rainfall Kinetic Energy (KE) was computed according to Wischmeier and Smith (1978), as well as EI30, the reference erosivity index, combining KE and I30, meaning I in the 30 min with maximum Intensity during the rainfall. Other erosivity indexes were computed using several P and I thresholds. The 10 years data series of P, I, KE, EI30 and maximum I for several durations were statistically treated at event, seasonal and year levels.

In this study event is defined as the period of precipitation prior to erosion and runoff data collection in the measuring devices at the outlet of each erosion plot. During 10 years, 167 events were recorded, 67 only generating runoff (named non-erosive events) and the remainder generating runoff and soil loss (erosive events).

Full details on the study site, experimental, data treatment and statistical procedures applied in the study can be found in Figueiredo (2001) and in later works by the first author (e. g., Figueiredo, 2015; Figueiredo *et al.*, 2021).

Results and Discussion

The annual global erosional response to rainfalls of the 5 plots along 10 years was low for both Runoff (R) and Soil Loss (SL) (Table 1), especially considering plots' steep slope gradient. These results are explained by the very rock fragment content and cover of plots' soil, limiting the development of erosive runoff events following most common rainfalls (Figueiredo, 2001; Poesen *et al.*, 1994).

However, differences in SL were found between plots (from 480 to 167 kg ha^{-1}) and, much sharper, between years (from 1907 to 55 kg ha^{-1}) (Figueiredo, 2001). Seasonal relative contributions to the annual totals show that R and P had a roughly similar seasonal pattern, while for SL the share of spring and summer to the annual total was much larger than that of P and R (Table 1).

Table 1. Annual average and seasonal distribution of Rainfall, Runoff and Soil Loss in the study plots.

Time period	Measured variables		
	Rainfall	Runoff	Soil Loss
Year totals	573 mm	22 mm	361 kg ha^{-1}
Relative seasonal distribution (% of the year)			
Autumn	34%	37%	9%
Winter	35%	35%	7%
Spring	25%	23%	55%
Summer	6%	5%	29%

Rainfall erosivity is the main factor explaining plots erosional response, accounting for about 50% of SL data variance. From all erosivity indexes computed, the best performing was EI30m, calculated with all rains (no intensity or height threshold). EI30m related at event level in a power function with SL (Figueiredo, 2001):

$SL = 0.306\ EI30m^{0.848}$ (r=0.713, N=100)

EI30m annual average was highly correlated with the original EI30, calculated for events above defined rainfall height threshold. Poorer correlations were found with Kinetic Energy (KE) and with P, best fits being obtained with a power function (Figueiredo, 2001):

$EI30m=2.529\ EI30^{0.884}$, r=0.996, N=10

$EI30m=2.044\ KE^{1.344}$, r=0.797, N=10

$EI30m=0.722\ P^{1.109}$, r=0.647, N=10

These results confirm that rainfall erosivity is far from being directly dependent on rainfall height alone and that kinetic energy alone does not entirely represent rainfall erosivity generating soil loss. In fact, the power relationship between SL and KE at event level has a lower correlation coefficient than that found for EI30m:

$SL=0.880KE^{1.207}$, r=0.699, N=100

On the other hand, SL related with I during erosive events, the correlation coefficient for 3h duration (r=0.704) falling between those found with EI30m and with KE. The exponent of the power function fitted to SL vs. I3h data was b=2.074. Actually, the best correlation coefficient of the power relation between SL and I was obtained for this 3h Rainfall duration, shorter and larger durations resulting in a lower correlation coefficient (Figure 1). For Quinta de Santa Bárbara, the 30 min rainfall duration, widely adopted as reference (Wischmeier and Smith, 1978), does not perform so well as that of the 3h.

As suggested by SL and R results, rainfall erosivity depicted seasonal changes (Table 2). For EI30m, autumn had the highest contribution for year total, while for KE the highest contribution was that of winter. The least contribution came from summer in both cases, the range of the seasonal distributions being larger for KE (37%-9%, against 32%-19% for EI30m). Although the reference year-based IDF curves were derived for the study site (Figure 2) changes in I for the same rainfall duration are evident along the year (Figure 3), and so seasonal IDF curves were also derived (Table 3). The main outcome of this analysis is that, for short duration rainfalls, intensities are higher in summer than in winter, and the opposite is found in longer rainfalls. This may be explained by the dominance of convective rain showers due to over-heating in hot summers, typical of Douro Region, while in winter frontal precipitations dominate, following the mid-latitudes atmospheric circulation. The 3h rainfall duration shows uniform behavior along the year, meaning that it be taken as the threshold for defining short and long durations at the study site.

Seasonality in precipitation shown by data presented above expresses the typical Mediterranean climate regime of the Douro Wine Region, with a clear dry summer, and the semi-arid domain prevailing at the study site (Aridity Index < 0.5; Figueiredo 2015). Results further show that seasonality in precipitation is also evident in the most relevant time domain (24 h to 5 min) for understanding the effect of rainfall characteristics on erosion processes (meaning rainfall erosivity). Although the EI30 cumulative curves along the hydrological year, e. g. as presented by Tomás (1997), for Alentejo, South Portugal, and by Figueiredo (2001), for Douro, provide an indirect appraisal of seasonality of rainfall erosivity, such information lacks in most mountain viticulture areas.

Table 2. Annual average and seasonal distribution of EI30m erosivity index, Kinetic Energy (KE), and Rainfall Intensity (I) at the study site.

Time period	Computed erosivity indexes	
	EI30m	KE
Year totals	796 MJ ha^{-1} mm h^{-1}	87 MJ ha^{-1}
Autumn	32%	29%
Winter	26%	37%
Spring	25%	25%
Summer	19%	9%

In any case, the relative seasonal distributions of erosivity indexes calculated are far from matching that of SL (Table 1). The main reason for this finding is that out of 167, 3 extreme erosion events accounted for 75% of the total soil loss in 10 years and were recorded in late spring-early summer. Such events introduced a very important bias in the event, seasonal and annual SL series (Figueiredo, 2001).

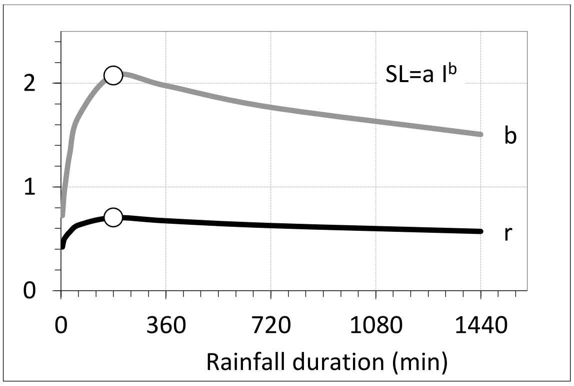

Figure 1. Changes with Rainfall duration in exponent (b) and correlation coefficient (r) of the power function relating Soil Loss (SL) with maximum Rainfall Intensidy (I) at event level. Maxima at 3h duration in blank dots.

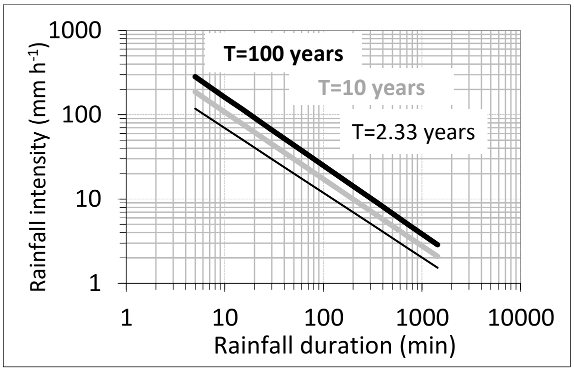

Figure 2. Intensidy-Duration-Frequency (IDF) curves for Quinta de Santa Bárbara study site (T, Return period,Gumbel distribution).

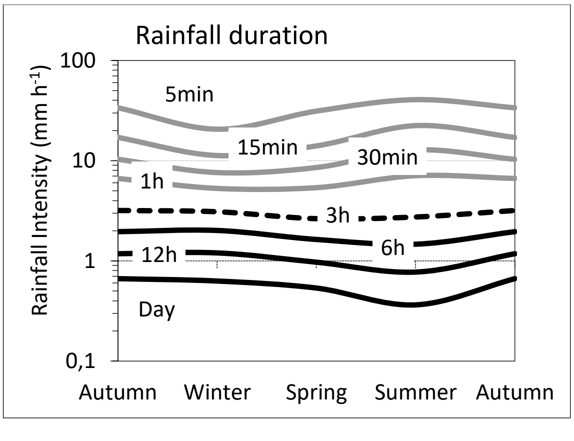

Figure 3. Seasonal variation of maximum Rainfall Intensity for several durations and for 2.33 years Return period.

These events are characterized in Table 4. They accounted for almost all of the respective year SL (>97%) and were triggered by heavy rainfalls. In fact, in the KE per event series these extreme soil loss records rank 8th, 23nd and 17th (in 167 events), respectively from the highest to the lowest SL (Table 4). In the EI30m series, extreme events rank is, in the same sequence, 1st, 10th and 16th, indicating even less frequent erosive rainfall characteristics at the origin of so large soil loss rates. Furthermore, EI30m event rank better matches that of SL, as compared to the KE event rank, meaning an important contribution of intensity to rainfall erosivity.

Table 3. Parameters of seasonal and year IDF curves ($I=at^b$, Return period, T, years; Intensity, I, mm h^{-1}; Duration, t, min; all r > 0.996).

T	I=at^b	Autumn	Winter	Spring	Summer	Year
100	**-b**	0.843**ac**	0.657 **b**	0.800 **a**	0.906 **c**	0.811 **a**
	a	891.5	383.6	763.4	1373.3	1043.4
50	**-b**	0.834 **a**	0.654 **b**	0.795 **a**	0.903 **c**	0.807 **a**
	a	770.9	336.8	667	1187	932.5
20	**-b**	0.818 **a**	0.647 **b**	0.785 **a**	0.896 **c**	0.801 **a**
	a	612.3	274.3	538.7	938.6	784.6
10	**-b**	0.802 **a**	0.640 **b**	0.774 **a**	0.888 **c**	0.794 **a**
	a	492.4	226	440	747.1	670.5
5	**-b**	0.778 **a**	0.629 **b**	0.759 **a**	0.876 **c**	0.785 **a**
	a	370.6	175.7	337.7	548	551.7
2.33	**-b**	0.733**ab**	0.605 **c**	0.726 **b**	0.846 **d**	0.767 **a**
	a	228.3	114	213.9	306.3	406.5

Note: Values followed by the same letter in lines are not significantly different (Tukey test, p 0.05; tests performed with log transformed values).

Maximum rainfall intensity during extreme erosion events ranged from 23.9, in the 3rd in rank, to 48.5 mm h^{-1}, in the 1st in rank, for 30 min duration (Table 4). This was actually the duration for which I ranking of the 3 extreme events matches that of SL. For shorter and longer durations, the 2nd event recorded peak rainfall intensities not matching its SL ranking. Except for the 5 min duration in the 1st and 2nd event, rainfall intensities were not impressively high. The maximum return periods of rainfall intensity for the respective season were, on the contrary, quite large: 19.1 years (3rd event), 22.3 (2nd), and 94.3 (1st). Rainfalls triggering the 3 events were quite different, as shown by the rainfall duration associated to the maximum return period: 1 h in the 3rd, 5 min in the 2nd, and 3 h in the 1st.

Peak intensity is associated to runoff initiation during erosive rainfalls (Morgan, 2005). Figure 4 depicts the average of maximum Intensity of the 3 extreme events for the 5 min to 24h rainfall duration interval is, which are expressively higher than those of the other 96 erosive events recorded in 10 years. In events that did not result in soil loss (non-erosive), Rainfall Intensities were far lower than those of the events producing Soil Loss. Differences in I between the 3 groups of events are better expressed for short rainfall durations (< 3h).

Extreme rains generated most of the large erosion events reported in vineyard areas (e. g., Martínez-Casasnovas and Ramos, 2006). Extreme erosion events were also reported in the Douro Wine Region (e. g., Pereira *et al.*, 2014). However, these resulted from the combined effects of surface and subsurface erosion processes during long rainfall periods. Furthermore, none of the mentioned works, all in Mediterranean mountain vineyards, episodes described occurred in late spring-early summer period.

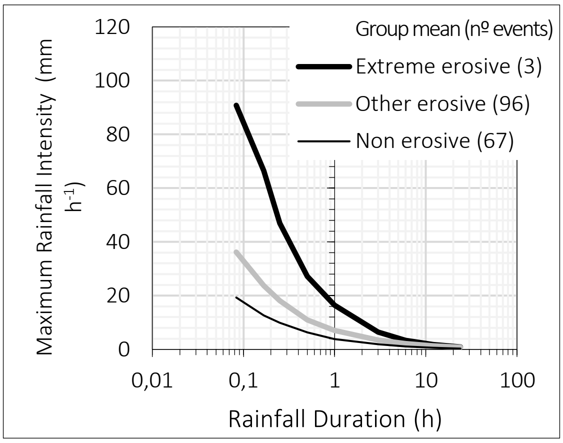

Figure 4. Comparison of Maximum Intensity recorded for different durations in extreme, erosive and non-erosive events (averages per group of events).

As expected for the month and season, vine canopies provided and increasingly higher cover from the 3rd to the 1st extreme event, when canopies were close to full cover in the vine row (Table 4). Therefore, extreme soil loss did not occur as a consequence of low vegetation cover in the vine rows. It should be noted that the maximum cover percentage allowed by vine rows is 62% of plot area, meaning inter-row lanes were the vineyard plot critical area for generating soil loss during erosive rainfalls. This was certainly the case in extreme soil loss events recorded, as total soil cover by vegetation (vine row and inter-row lane weighted average cover) ranged from 27% to 51% (3rd and 1st, respectively), providing poor soil protection.

Maximum cover fraction by canopies in vine rows is directly dependent on plant density and, therefore, on the plantation scheme adopted at vineyard installation. Lower vine row cover fractions mean also larger inter-row lanes. In these, effective erosion control depends on tuned soil management practices (up to 70% reduction in soil loss according to Figueiredo, 2015). This is an increasingly demanding requirement as vine plant density lowers (Figueiredo *et al.*, 2020) and as the worst case scenario is targeted when designing vineyard conservation measures. Results presented above clearly outline that such design criterion is useful to cope with large return period rainfalls resulting in even rarer soil loss events.

Table 4. Season, rainfall and vegetation cover conditions during extreme erosion events in the study site (Sp – Spring; Su – Summer).

Parameter	**EXtreme Soil Loss events**		
Event Soil Loss rank	3rd	2nd	1st
Month/Season	May/ Sp	June/ Sp	July/Su
Soil Loss(kg ha^{-1})	764	804	1058
Kinetic Energy (MJ ha^{-1})	13.26	9.79	19.07
EI30m (MJ ha^{-1} mm h^{-1})	175	188	539
Event Maximum Rainfall Intensity for duration x (Ix)			
I3h (mm h^{-1})	7.4	6.0	9.3
I1h (mm h^{-1})	19.7	15.2	24.8
I30min (mm h^{-1})	23.9	30.4	48.5
I5min (mm h^{-1})	24.0	180.0	141.6
*Return Period of Rainfall Intensity for duration x (T_{Ix})**			
T_{I3h} (years)	13.8	3.8	94.3
T_{I1h} (years)	19.1	6.0	16.9
T_{I30min} (years)	4.4	10.8	16.8
T_{I5min} (years)	0.6	22.6	9.9
Vagetation cover fraction (C, total and in vine row)			
Crow (0 – 1.00)	0.43	0.71	0.83
Ctotal (0 – 0.62)	0.27	0.44	0.51

* Based on the respective seasonal series of event Rainfall Intensity (each event maximum painted gray).

Conclusions

Seasonality of precipitation that is typical of the Mediterranean climate prevailing in Douro Wine Region is also present for very short time domains of analysis of rainfall series. Rainfall intensity for durations below 3h is higher in summer than in winter, the opposite being found for larger rainfall durations.

Low frequency high erosivity rains falling in late spring – early summer were responsible for extreme erosion events accounting for 75% of total soil loss recorded in 10 years. Rainfall erosivity is the main factor explaining plots erosional response (50 % of soil loss data variance). EI30m was the best performing erosivity index, either for the entire soil loss series or for that of the extreme erosion events.

Vine rows cover provided by actual plantation schemes in the Douro Region require complementary conservation concerns through tuned soil management practices in the inter-row lanes, as the conventional ones result insufficient to keep soil loss at tolerable rate during high erosivity rainfalls.

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