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Research papers

Soil erosion after fire in volcanic terrain: Assessment and implications for post-fire soil losses

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A R T I C L E I N F O

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A B S T R A C T

Wildfires can dramatically modify the hydrologic and erosion response of ecosystems, increasing risks to population and assets downslope of fire affected hillslopes. This applies especially to volcanic areas in fire-prone regions which often exhibit steep terrain and high population densities. However, the effects of fire on key hydrologic and erosion parameters, which are critical for modelling runoff-erosion processes, predicting related post-fire risks and for selecting effective mitigation measures, have not been extensively assessed in this terrain type. Here we evaluate water erosion processes of two contrasting volcanic soils in recently burned forest areas of Tenerife (Canary Islands, Spain) at hillslope scale using erosion plots monitoring and rill erosion simulation experiments. The results show that both the lithology and the degree of weathering of the volcanic material govern the post-fire water erosion by concentrated flow (rill erosion experiments) and by the combination of interrill and rill erosion (erosion plots). Mature volcanic soils showed less susceptibility to erosion than weakly weathered volcanic soils and soils with non-volcanic lithologies. The results also show that the availability of easily detachable and transportable soil particles swiftly decreases after the fire, leading to the exhaustion of sediments and a decrease of the erosion rates with cumulative runoff events. These findings have direct implications for the modelling of runoff-erosion processes in volcanic terrain.

1. Introduction

Wildfires can alter key components of ecosystems, modifying the runoff and erosion response of burned areas (Shakesby and Doerr, 2006) with, sometimes, severe on– and off-site effects (Hosseini et al., 2016; Niemeyer et al., 2020; Nyman et al., 2015; Rhoades et al., 2019). In addition to its effect on the vegetation and the litter layer that protect the soil (DeBano et al., 1998; Keeley, 2009; Ryan and Noste, 1983; Shakesby and Doerr, 2006), fire can also directly affect the erodibility of soil by promoting soil aggregate breakdown (Alcañiz et al., 2018; Giovannini and Lucchesi, 1983; Jordán et al., 2011; Mataix-Solera et al., 2011) and induce or enhance existing soil water repellency (Agbeshie et al., 2022; Doerr et al., 1996; Keizer et al., 2008; Robichaud et al., 2016). These alterations can decrease the soil infiltration rate, water storage capacity, and resistance of soil to erosion, thereby enhancing runoff and soil loss (Agbeshie et al., 2022; Alcañiz et al., 2018; Shakesby and Doerr, 2006). The magnitude of these changes and the subsequent hydrologic and erosion response of the ecosystems, however, is highly variable (Moody and Martin, 2009) and depends not only on the behaviour and effects of the fire, but also on the characteristics of the soil and the ecosystem as a whole including its climatic conditions, topography, resilience to fire and the time elapsed after fire (Sheridan et al., 2016; Vieira et al., 2015; Wagenbrenner and Robichaud, 2014). For particular combinations of soil burn severity and soil type, and together with rainfall and topographic scenarios, severe runoff-erosion events with on– and off-site consequences can be expected until more stable soil and land cover conditions return (Calkin et al., 2007; Hohner et al., 2019; Moody et al., 2013).

These processes are relevant also in terrain with volcanic soils, which cover more than 124 million hectares of the Earth surface (Neall, 2006). When undisturbed, mature volcanic soils are often considered to be less susceptible to erosion than weakly weathered volcanic soils and other soil types developed over non-volcanic lithologies (Dahlgren et al., 2004; Nanzyo et al., 1993a). Undisturbed mature volcanic soils show high water retention capacity, infiltration rate and soil aggregate stability (Dahlgren et al., 2008; Dahlgren et al., 2004; Nanzyo et al.,

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1993a). This enhanced stability against erosion allows the development of deep soil profiles even on steep slopes when protected by the dense vegetation they usually support (Nanzyo et al., 1993b). These typically very productive soils (Shoji et al., 1993; Soil Survey Staff, 1999), often support densely populated communities in favourable climates (Mohr, 1938; Papale, 2015; Small and Naumann, 2001). The reduced susceptibility to erosion of undisturbed mature volcanic soils, however, contrasts with the higher susceptibility to erosion of weakly weathered soils derived from recent volcanic deposits or developed in temperate or seasonally dry conditions (Dahlgren et al., 2004; Poulenard et al., 2001). The latter usually show coarser texture, lower porosity and soil aggregate stability (Dahlgren et al., 2004; Poulenard et al., 2001; Tejedor et al., 2013) mainly due to the weaker development of andic properties of these soils that are usually developed from recent volcanic ejecta or in climatic conditions that limit the weathering process (Dahlgren et al., 2004).

Disturbances such as fires can dramatically change the status of ecosystems in general (Larsen et al., 2009; Prats et al., 2019; Vieira et al., 2018) and of volcanic soils in particular (Kimble et al., 2000; Neris et al., 2013a) mainly by reducing ground cover protection. Following fire both weakly weathered and mature deep volcanic soils can become more prone to erosion, particularly on steep terrain, sometimes with severe effects. Previous studies have described severe flooding and erosion events during intense rainstorms following fires, for example, in La Palma 2009 (Spain) (Neris et al., 2016) and Sarno Mountains 2012 and Mt Salto 2017 (Italy) (Esposito et al., 2017; Esposito et al., 2019). Such events may be especially a threat in tropical and subtropical regions where intense rainstorms are common (El-Swaify et al., 1982).

Understanding erosion from surface runoff after wildfires is key to modelling and predicting the ecosystem runoff-erosion response, anticipating risks, and implementing effective erosion mitigation actions in the post-fire period (Robichaud, 2005). Interrill erosion processes (e.g. sheetwash) after fire have been studied in some detail at point or plot scale (0.1 – 2 m^2) using rainfall simulations in volcanic soils of South-America (Morales et al., 2013; Poulenard et al., 2001), Europe (Neris et al., 2017; Neris et al., 2013a) and the USA (Laflen et al., 1991; Robichaud et al., 2016). However, at hillslope or catchment scale, rill erosion processes associated with concentrated flow are often those that are dominant and most destructive following fire (Lei et al., 1998; Meyer et al., 1975; Mutchler and Young, 1975; Pierson et al., 2009; Prats et al., 2019), and thus, must be correctly understood and modelled in order to predict erosion risk at those scales. To the authors' knowledge, field experiments with concentrated flow to simulate and model rill erosion and soil loss at hillslope scale in volcanic terrain following wildfires have been conducted exclusively in the USA (Robichaud et al., 2010; Wagenbrenner et al., 2016; Wagenbrenner et al., 2010) on a very specific volcanic soil type in a temperate climate: weakly weathered ash-cap soils developed over non-volcanic lithologies affected by Holocene tephra deposits from the eruption of Mount Mazama (7600 cal. years B. P.) (McDaniel et al., 2005). This volcanic soil type exhibits different properties and thus likely runoff-erosion responses than other volcanic soils worldwide that are derived solely from volcanic material. For example, Biteete-Tukahirwa (1995) reported that deep volcanic agricultural soils in Western Uganda had infiltration rates in excess of 1500 mm h^{-1}, compared to agricultural ash-cap soils in the western USA where infiltration rates ranged from 10 to 40 mm h^{-1} (Elliot et al., 1989). Thus, we hypothesize that the specific results obtained in the previous studies on rill erosion in the USA might not be representative of those of the weakly weathered or mature soils developed on pure volcanic material and that it is, therefore, unclear if they can be used to accurately model and predict erosion in other volcanic soils worldwide.

This study addresses this research gap with the main objectives of (1) characterizing and comparing rill erosion processes for fire-affected mature and weakly weathered soils derived exclusively from volcanic material, and (2) quantifying soil loss at hillslope scale for these soil types in the post-fire period. It thus aims to provide new insights that can help to model runoff-erosion response of other fire-affected volcanic terrain.

2. Methods

2.1. Study areas

We selected two study areas with two common, but contrasting climatic (dry vs humid subtropical climates) and soil characteristics (weakly weathered vs mature volcanic soils) in recently burned forest areas of Tenerife (Canary Islands, Spain). Tenerife is a volcanic island of 2,057 km^2 located between 27°55′ and 28°35′ N and between 16°05′ and 16°55′ W and with a maximum elevation of 3,718 m (Fig. 1 and Table 1). These two study sites provided the opportunity to evaluate erosion process at hillslope scale for two contrasting fire-affected volcanic soils (mature vs weakly-weathered) and comparing the results with other soil types developed in non-volcanic lithologies.

At the study area Vilaflor, soils are weakly weathered Andic Dystroxerepts (Soil Survey Staff, 1999) (Fernández Caldas et al., 1982) derived from 1.6 to 0.7 million-year-old phonolite lava flows. Mean annual temperature is 13.9 °C and mean annual precipitation is 300 mm with large interannual variations (from 50 mm to 520 mm) (2010–2020 data from the Topos weather station: 28°10′18'' N, 16°39′05'' W, 1830 m; ~ 1.7 km S of the site). A fire ignited on 10 June 2015 affected 25-ha of a young and dense stand of Canary Island pine (*Pinus canariensis*) at an elevation between 2025 and 2225 m with slope gradients ranging from 40 to 75 %. The area was previously burned in 1998. A previous assessment of the soil burn severity conducted in the same area after the same fire showed that the fire consumed approximately 90 % of the forest floor (visual assessment on 1 m^2 plots, 60 replicates), partially consumed the tree canopies, and produced primarily black ash with some patches of grey ash. The soil structure and roots were only slightly affected, and the post-fire soil water repellency (Water Drop Penetration Time - WDPT- test) (Doerr, 1998) was extreme (Neris et al., 2017) (Table 1).

At Candelaria, soils are mature Typic Haplustands (Soil Survey Staff, 1999) (Fernández Caldas et al., 1982) derived from 0.7 to 0.01 million-year-old basaltic pyroclasts and 2.6–0.7 million-year-old basaltic lava flows. Mean annual temperature at the nearest climate station is 12.1 °C and mean annual precipitation 740 mm, ranging from 150 mm to 1500 mm (2009–2020 data from the Gaitero station: 28°23′41'' N, 16°26′00'' W; 1750 m, ~ 0.7 km NE of the site). A fire starting on 31 July 2015 burned 5 ha of a mature Canary Island pine (*Pinus canariensis*) forest stand located between 1400 and 1700 m in an area with a slope gradient ranging from 25 to 55 %. There are no records of previous fires in the area in the last 50 years. A previous assessment of the soil burn severity conducted in the same area after the same fire showed that the fire consumed 85 % of the litter layer (visual assessment on 1 m^2 plots, 30 replicates), partially scorched the pine canopies and produced mainly black ash with few patches of grey ash. The fire had a limited impact on the soil structure and roots, and post-fire soil water repellency (Water Drop Penetration Time - WDPT- test) (Doerr, 1998) was negligible (Neris et al., 2017)(Table 1).

Both the fires at Vilaflor and Candelaria resulted in low to moderate soil burn severity, determined based on a combination of soil burn severity indicators (ground cover, ash colour and depth, soil structure, roots, and soil water repellency) (Parsons et al., 2010). However, when considering loss of ground cover, a key parameter determining erosion response after fires (Larsen et al., 2009; Prats et al., 2019; Vieira et al., 2018) including in volcanic soils (Neris et al., 2013a), the impact corresponds to that of a high severity fire according to Parsons et al. (2010).

2.2. Evaluating rill erosion

We conducted rill experiments to assess erosion by concentrated flow following a modification of the protocol described by Robichaud et al.

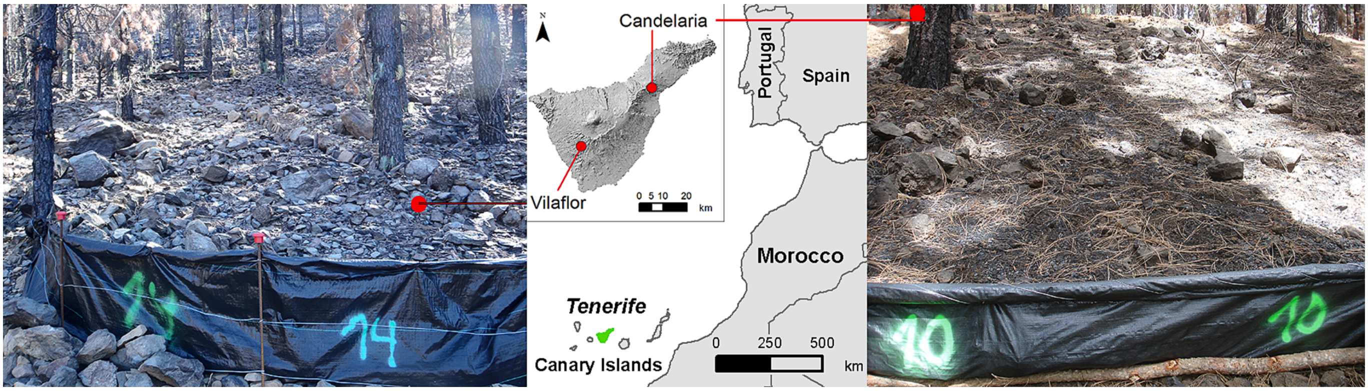

Fig. 1. Location and views of the Vilaflor (upper left) and Candeleria (upper right) 2015 wildfire study sites and hillslope erosion plots on the Canary Islands (Spain).

Table 1
Site, rill plots, erosion plots and rainfall characteristics (mean and standard deviation for the rill and erosion plots characteristics) for the 4-year study (July 2015 – July 2019) after the 2015 Candelaria and Vilaflor wildfires. Ground cover measured 1 month after the fire. Extreme soil water repellency refers to water drop penetration time values greater than 1 h (Doerr et al., 1996) according to a previous study in the area after the same forest fires (Neris et al. 2017).

Site characteristics	Candelaria	Vilaflor
Elevationv above sea level (m)	1400–1700	2000–2250
Mean annual temperature (°C)	12.1	13.9
Mean Annual Precipitation (mm)	740	300
Dominant tree species	Dense pine forest stand (*Pinus Canariensis*)	
Slope steepness (%)	40–75	25–55
Ground cover 1 month after the fire (%)	25–50	40–70
Soil type (depth of the soil profile -m-)	Haplustands (0.9)	Dystroxerepts (0.4)
Soil texture (% sand, silt, clay)	Loam (42, 46, 12)	Loam (48, 39, 13)
Rock fragment cover and content (%)	25–25	53–43
Soil burn severity	Low-moderate	Low-moderate
Forest floor consumption	High	High
Soil water repellency	None	Extreme
Rill plots characteristics		
Number of plots (simulations)	4 (16)	6 (24)
Slope steepness (%)	60 ± 6	40 ± 4
Ground cover 1 month after the fire (%)	38 ± 6	57 ± 16
Erosion plots characteristics		
Number of plots	5	10
Area (m^2)	36.9 ± 5	36.0 ± 6
Slope steepness (%)	56 ± 10	44 ± 5
Ground cover 1 month after the fire (%)	40 ± 10	61 ± 12
Days with rain over the study period	384	135
Mean annual precipitation depth (mm)	678 ± 80	199 ± 79

(2010) and previously used in numerous studies aiming at characterizing rill erosion process (Pierson et al., 2009; Pierson et al., 2008; Robichaud et al., 2013a; Robichaud et al., 2020; Wagenbrenner et al., 2016; Wagenbrenner et al., 2010). We installed 6 rill plots at Vilaflor and 4 at Candelaria prior to any erosion event (Table 2). The larger burned area at Vilaflor provided more opportunities to find locations with similar characteristics for the rill experiments. Rill plots were unbounded 4 m long sections of the slope. An energy dissipater box was placed on the top of the plot to supply concentrated flow at 4 sequential controlled water inflow rates (12, 24, 36, and 48 L min^{-1}) for 12 min each (48 min per experiment) to each plot with no dry spell between them. A V-shaped metal sheet (25 cm wide and 60 cm long) was inserted into the soil at the end of the plot to collect runoff. Flat sheet metal was used to redirect the flow to the outlet where needed. Six timed runoff samples (collection period ranging from 30 to 60 s) were collected sequentially for each flow rate with approximately 1 min interval between them in plastic bottles (500 mL or 2 L depending on flow rate). Following previous studies (Pierson et al., 2008; Robichaud et al., 2013a; Robichaud et al., 2020; Robichaud et al., 2010; Wagenbrenner et al., 2016), these samples were split in two sets, 3 of them from the first half (collected between minutes 0 and 6) and 3 of them from the second half of the simulation (collected between minutes 7 and 12). The first set of samples collected for each simulation are considered to be representative of the initial runoff and erosion condition, which usually shows higher and more variable runoff and erosion rates, whereas the second set represents the steady-state condition where both runoff and erosion rates stabilize (Elliot et al., 1989). The samples were then weighed, dried (105 °C for 48 h) in glass beakers, and weighed again to calculate runoff volume, soil loss and sediment concentration. Average values of runoff rate, sediment flux rate, and sediment concentration for each condition and per simulation combining all flow rates (initial, steady-state and average conditions) were calculated from those two sets of timed runoff samples. Runoff velocity of the flow profile was measured twice, during the initial and the steady-state condition (minutes 3 and 9), for each inflow rate. A saturated calcium chloride solution (5 mL per measurements) and two conductivity probes at 1 and 3 m from the top of the plot were used to calculate the average runoff velocity for each condition as the distance between probes divided by the time difference between the maximum conductivity readings on each probe. For each experiment, flow width and depth (5 measurements along the flow width) were measured twice (minutes 3 and 9) at 1 and 3 m from the top of the plot using a tape measure. The mean values of the parameters obtained for each condition were calculated by combining all the measurements taken per flow rate and simulation.

2.3. Erosion monitoring at hillslope scale

Ten hillslope erosion plots were installed to monitor erosion at hillslope scale at Vilaflor and 5 at Candelaria prior to any erosion event following Robichaud and Brown (2002) (Table 1). All erosion plots were located near to, but separate from, the rill plots described in 2.2. As was the case for rill experiments described above, the larger area burned at Vilaflor provided more opportunities to install erosion plots in areas of similar characteristics at this site. The areas selected for plot installation were representative of the slope gradient and ground cover of their respective burned area. At Candelaria, the plots were installed in steeper terrain than at Vilaflor (average slope 56 vs 44 % respectively), but the slope gradient was homogeneous within sites and similar to that for the rill experiments. The plots at Vilaflor had higher ground cover than at Candelaria (61 vs 40 %). Plot width (3.9 vs 3.6 m at Vilaflor and Candelaria respectively), length (10.2 vs 10.3 m), and area (36.0 vs 36.9 m^2) were homogenous within and similar between sites, and in the range recommended by Robichaud and Brown (2002) to measure interrill and rill erosion at hillslope scale.

Silt fences built with geotextile fabric were installed at the downhill

Table 2
Mean and coefficient of variation (CV) of the rill experiment results for the initial (In), steady state (SS) and the average conditions (Mean) for the 2015 Candelaria (n = 16) and Vilaflor (n = 24) wildfires. Different numbers in brackets show statistically significant differences between sites and different letters statistically significant differences between conditions (initial 'In'- vs steady state 'SS') according to the GLMM results.

Site		Runoff rate $L\ min^{-1}$			Runoff velocity $m\ s^{-1}$			Sediment flux rate $kg\ s^{-1} \times 10^{-3}$			Sediment concentration $kg\ L^{-1} \times 10^{-3}$			Flow depth mm			Flow width m		
		In	SS	Mean	In	SS	Mean	In	SS	Mean	In	SS	Mean	In	SS	Mean	In	SS	Mean
Candelaria	Mean	8.9	9.7	9.3	0.13	0.13	0.13	0.41	0.07	0.24	1.35	0.26	0.75	4.8	5.1	5.0	0.25	0.25	0.25
	CV	0.99	0.95	0.97	0.61	0.58	0.59	0.89	1.00	0.90	0.90	1.05	0.93	0.82	0.73	0.77	0.66	0.62	0.64
		(1 a)	(1 a)	(1)	(1 a)	(1 a)	(1)	(1 a)	(1 a)	(1)	(1 a)	(1 a)	(1)	(1 a)	(1 a)	(1)	(1 a)	(1 a)	(1)
Vilaflor	Mean	27.6	30.7	29.1	0.14	0.16	0.15	2.96	0.61	1.79	8.11	1.47	4.09	11.6	11.1	11.4	0.62	0.61	0.62
	CV	0.65	0.56	0.60	0.40	0.44	0.42	0.85	0.74	0.82	0.61	0.59	0.52	0.19	0.20	0.19	0.08	0.12	0.10
		(2 a)	(2 a)	(2)	(1 a)	(1 a)	(1)	(2 a)	(2b)	(2)	(2a)	(1 a)	(2)	(2 a)	(2 a)	(2)	(2 a)	(2 a)	(2)

end of the erosion plots. Sediments trapped by the silt fences were collected and weighed after erosion events (cleanouts). Subsamples were taken and oven-dried at 105 °C for 48 h to calculate moisture and dry mass of the eroded sediments. Total rainfall, 10-minute maximum rainfall intensities (I_{10}), soil loss, and specific soil loss per mm of rainfall were calculated for those cleanouts from weather stations nearby (see section 2.1 for details). We monitored erosion processes from natural rainfall for 4 years after the fire to capture the recovery of erosion dynamics after the fire. Soil loss results were combined by year to provide annual values, where year 1 was within the first year after the fire (Aug 2015 – July 2016) and subsequent years were within year 2 (Aug 2016 – July 2017), year 3 (Aug 2017 – July 2018), and year 4 (Aug 2018 – July 2019). Rainfall amounts and intensity were monitored at the nearby weather stations representative for the study sites described in 2.1.

2.4. Statistical analysis

Differences between erosion responses calculated from the rill experiment data (runoff rate, runoff velocity, sediment flux rate, sediment concentration, flow depth and flow width) and hillslope erosion plots (soil loss and specific soil loss per mm of rainfall) were tested using a generalized linear mixed model (GLMM) with the parameters (average values per condition) as dependent variables (SPSS Inc., 2012). For rill erosion analysis, site (Candelaria vs Vilaflor), flow rate (12 vs 24 vs 36 vs 48 L min^{-1}), condition (initial vs steady-state) and they interaction were set as fixed factors. Plots were set as random factor and samples for each flow rate as repeated measurements. For hillslope erosion analysis, site (Candelaria vs Vilaflor), year (years 1, 2, 3, and 4) and their interaction were set as fixed factors. Plots were set as random factors and cleanouts as repeated measures. The GLMM analysis was repeated for the soil loss at the erosion plots including precipitation between cleanouts as random factor to specifically evaluate the effect of soil type on soil erosion in two contrasting climates. The Sidak test (Šidák, 1967) was used when significant statistical difference were found and multiple comparisons were needed (flow rates for rill experiments and years for erosion plots). Correlations between hillslope erosion parameters with other variables such as rainfall depth, I_{10}, mean I_{10}, ground cover, days after fire and year were examined by Pearson correlation coefficient (r). A significance level of 0.05 was chosen to indicate significant statistical differences. To compare trends over time in rill experiment data for all flow rates, a min–max normalization (rescaling) was used to make the data comparable.

3. Results

3.1. Rill erosion

At Vilaflor, all the plots produced runoff for all the inflow rates applied (12, 24, 36, and 48 L min^{-1}). At Candelaria, however, only one plot produced runoff for all the inflow rates applied, one plot for inflow rates 24, 36, and 48 L min^{-1}, one plot produced runoff for inflow rates 36 and 48 L min^{-1}, and one plot did not produce runoff. Accordingly, the coefficients of variation of the runoff and erosion variables were higher at Candelaria than at Vilaflor for all the variables measured (Table 2). In general, the coefficient of variation was also higher for the values at the initial condition than that of the steady-state condition. Only the sediment flux rate and the sediment concentration showed higher variability at the steady-state condition than that at the initial condition for Candelaria.

According to the GLMM results, the average runoff rate at Vilaflor was significantly higher than that at Candelaria for the steady-state condition and close to the average inflow rate (30.7 vs 9.7 L min^{-1}) (Table 2) despite the higher average slope and lower average ground cover of the latter (Table 1). This significant difference was also found for the initial and average conditions. Average runoff velocity was similar at Vilaflor and at Candelaria for the steady-state (0.16 vs 0.13 m

s^{-1}), and also for the initial and average conditions. The flow at Vilaflor was on average 117 % deeper (0.61 vs 0.25 m) and 143% wider than that at Candelaria for the steady-state (11.1 vs 5.1 mm) and for the initial and average conditions (Table 2). These differences were statistically significant for all conditions.

The average sediment flux rate at Vilaflor was significantly higher than that at Candelaria for the steady state, initial and average conditions. The sediment concentration showed statistical differences among sites for the initial and average conditions but not for the steady state condition according to the GLMM results.

As expected, average sediment flux rate and sediment concentration decreased considerably from the beginning to the end of each inflow rate application at both sites (Fig. 4). The sediment flux rate and concentration for the initial condition were almost five- and six-fold that for the steady state condition at Vilaflor and Candelaria respectively (Table 2). However, statistically significant differences between the initial and steady-state condition were only found regarding the sediment flux rate at Vilaflor (Table 2) probably due to the high variability found at Candelaria. Runoff rate and velocity remained almost constant during each rill experiment with constant inflow rate for both sites (Fig. 4).

When evaluating the rill parameters at the steady state condition for increasing inflow rates (12, 24, 36 and 48 L min^{-1}) (Fig. 5), Vilaflor showed statistically significant higher average values of runoff rate and sediment flux than Candelaria for all inflow rates evaluated. The average sediment concentration at Vilaflor was significantly higher only for 12 and 24 Lmin^{-1} inflow rates, whereas runoff velocity was comparable in all cases between both sites. The runoff rate gradually increased at both sites with increasing inflow rate (from 12 to 48 L min^{-1}). However, this increase between inflow rates was more pronounced at Vilaflor, where the slope of the runoff increase was almost two-fold that for Candelaria ($m = 1.1$ and 0.6 at Vilaflor and Candelaria respectively, Fig. 5). Consequently, the difference in runoff rate between the lowest and the highest inflow rates was statistically significant at Vilaflor but not at Candelaria, where the variability is higher. When comparing runoff velocity, both sites showed a similar increase with increasing inflow rates with significant differences between the lowest and the highest inflow rates (154 and 515 % for Vilaflor and Candelaria). Although increasing inflow rate promoted an increase in runoff rate and velocity, the sediment flux rate and concentration did not change significantly with increasing inflow rates at Candelaria and even decreased at Vilaflor (Fig. 5).

3.2. Erosion processes at hillslope scale

During the study period (4 years), 650 mm of precipitation were recorded at Vilaflor (with 135 days with rain) and 2644 mm at Candelaria (with 384 days with rain) (Tables 3 and 4 and Fig. 2). According to the GLMM results, the difference in precipitation was statistically significant. We found no statistically significant difference in the total soil loss over the study period between Vilaflor and Candelaria (3.9 and 3.8 T ha^{-1} respectively) (Tables 3 and 4) even when precipitation depth and I_{10} (except I_{10} for year 3) were higher each year and over the study period at the latter (Tables 3 and 4 and Fig. 3). Soil loss, however, was significantly higher at Vilaflor when compared to Candelaria in years 2 and 3 but not in years 1 and 4. The values of specific soil loss per mm of rainfall were higher at Vilaflor for all years evaluated.

When annual precipitation was not considered, soil loss remained almost constant at Vilaflor for years 1, 2 and 3 (ranging from 26 to 37 % of the total per year) and significantly decreased in year 4 (<5 %), the year with the lowest annual precipitation depth and I_{10} (Fig. 3 and Table 3). When precipitation was considered in the statistical analysis, however, year 4 showed significantly lower soil loss than that in the previous years whereas year 1 showed significantly higher values of soil loss than the subsequent years. Most of the erosion at Candelaria occurred in year 1 (52 %) (Fig. 3 and Table 4), with this difference being statistically significant when annual precipitation was not considered. When it was considered, differences between years were not statistically significant.

At Vilaflor, soil loss values for the cleanouts were more closely related to precipitation properties of the recorded storms for that period ($r = 0.71$ for precipitation depth, $r = 0.70$ for mean I_{10}, and $r = 0.40$ for I_{10}) than at Candelaria (only $r = 0.40$ for I_{10}) (Table 5). Specific soil loss per mm of rainfall was influenced by precipitation characteristics at both sites ($r = 0.38$ for mean I_{10} at Vilaflor and $r = 0.29$ for mean I_{10} at Candelaria). At the later, however, the days after the fire also influenced the specific soil loss per mm of rainfall ($r = -0.32$).

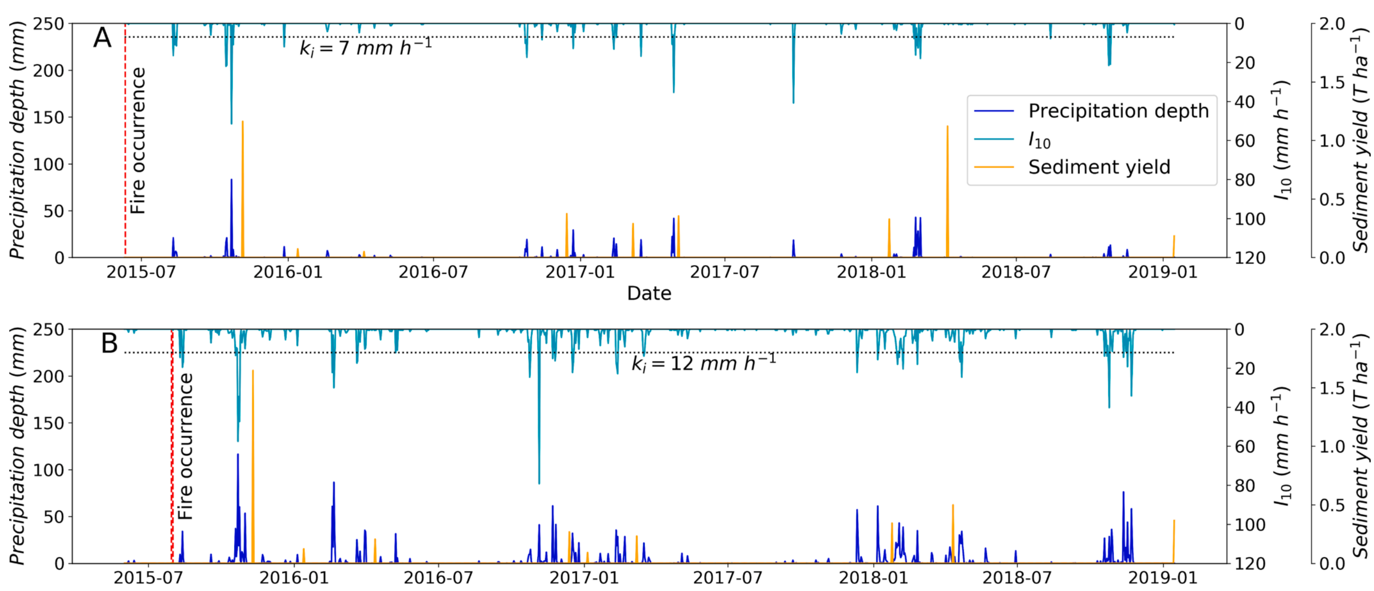

Fig. 2. Characteristics of the rain events (precipitation depth and 10-minute maximum rainfall intensity - I_{10}) and average sediment removed from the hillslope erosion plots during the study period (July 2015 to July 2019) for the Vilaflor (A) and Candelaria (B) wildfires.

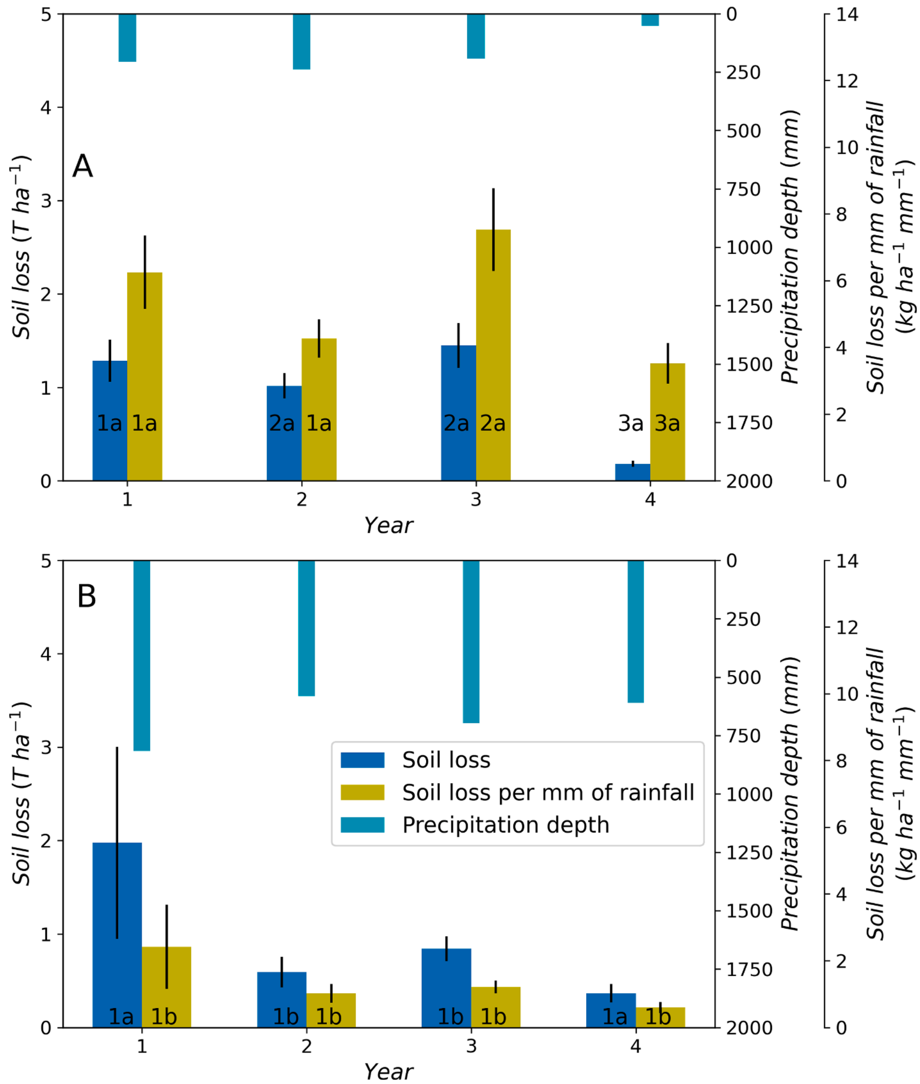

Fig. 3. Annual rainfall, and total soil loss and soil loss per mm of rainfall as determined from the hillslope erosion plots following the 2015 wildfires at Vilaflor (A) and Candelaria (B). Different numbers in the figure show statistically significant differences between years (years 1 to 4) and different letters statistically significant differences between sites (Vilaflor vs Candelaria).

4. Discussion

4.1. Post-fire rill erosion in volcanic soils

The runoff rate obtained for the rill experiments in this study (Table 2) at Vilaflor (29.1 L m^{-1}), characterised by weakly weathered soil, was greater than at the mature volcanic soil at Candelaria (9.3 L m^{-1}) and that reported in studies from the weakly weathered ash-cap soil in the USA (7.1 – 21 L m^{-1}; Table 6). The greater runoff at Vilaflor can be one of the reasons that flow here was wider and deeper (0.62 m and 11.4 mm) than at Candeleria (0.25 m and 5 mm) or in the USA for weakly weathered ash-cap soils (0.22 – 0.54 m and 0.7–9.7 mm; Table 6). The contrasting soil texture and related structural stability of both volcanic soils could also help to explain the rill's shape. Silt loam volcanic ash soils, as described by Robichaud et al. (2010), usually tend to have narrower incising rills than the coarser volcanic soils at Vilaflor. Additionally, soils at Vilaflor showed a low aggregate stability as reported by Neris et al. (2017) in a previous study in this specific site after the same fire. In this type of soils, rills usually widen as a result of the low stability of the rill's side-walls (Elliot and Laflen, 1993). At Candelaria, runoff rates were a third of those at Vilaflor (9.3 vs 29.1 L min^{-1}) probably due to the negligible soil water repellency of this mature soil after the fire, a situation previously described for this specific site and fire (Neris et al., 2017) and for other burned mature volcanic soils (Neris et al., 2013a). Rills at Vilaflor and Candelaria were broadly comparable in flow width and depth to those reported for studies in weakly weathered ash-cap soils of the USA (Table 6). According to Moffet et al. (2007), the width values we obtained for both Vilaflor and Candelaria are larger than those usually observed in field experiments, and typical of scenarios with limited supply of sediments (Foster, 1982). Despite the steeper terrain at Candelaria, runoff velocity at Vilaflor was similar to that at Candelaria. Both the high flow rate and velocity at Vilaflor were probably due to the extreme soil water repellency observed previously at the same site and after the same fire (Neris et al., 2017). This enhanced water repellency has been commonly reported for unburned (Dec et al., 2017; Neris et al., 2013b; Regalado and Ritter, 2005) and burned volcanic soils (Morales et al., 2013; Neris et al., 2013a; Poulenard et al., 2001) and can induce greater runoff rates (Prats et al., 2016a; Shakesby and Doerr, 2006) and, thus, higher runoff velocities. The presence of this extreme water repellent soil layer can also explain the lower variability of the parameters evaluated at Vilaflor when compared that to Candelaria, although the variability in both sites was in the range of that reported by previous authors using the same methodology (Pierson et al., 2009; Pierson et al., 2008; Robichaud et al.,

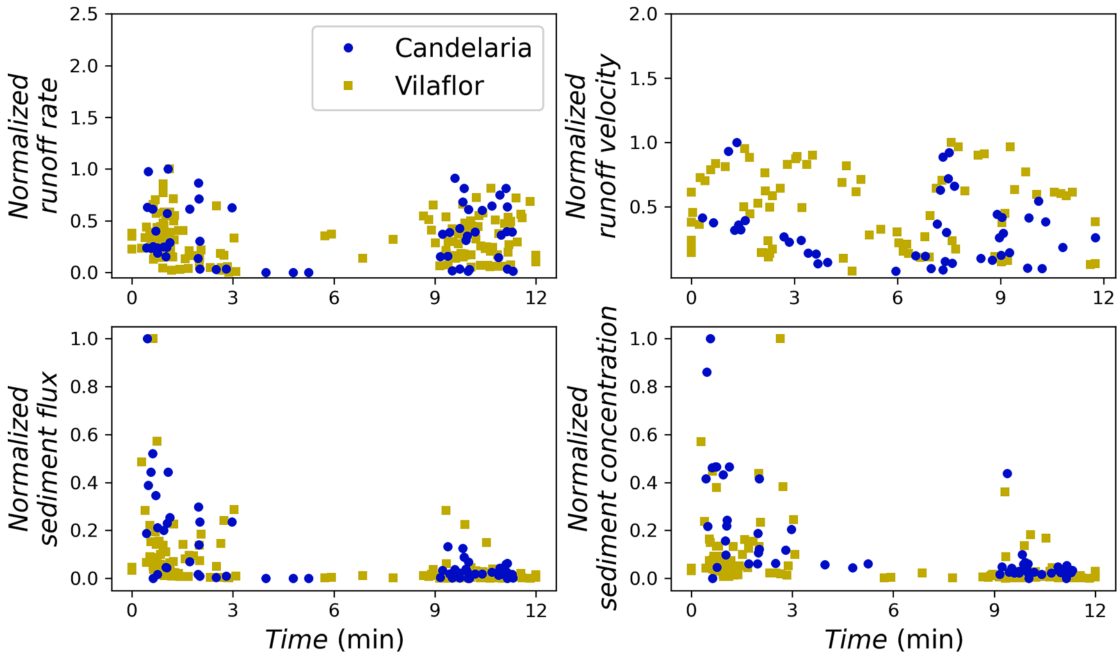

Fig. 4. Normalized rill properties during rill simulations (12 min) for the Candelaria (n = 96) and Vilaflor (n = 144) post-fire plots. Normalized parameters are the ratios of the parameter values minus the parameter minimum value to the difference between the parameter maximum and minimum values for the corresponding site and flow rate.

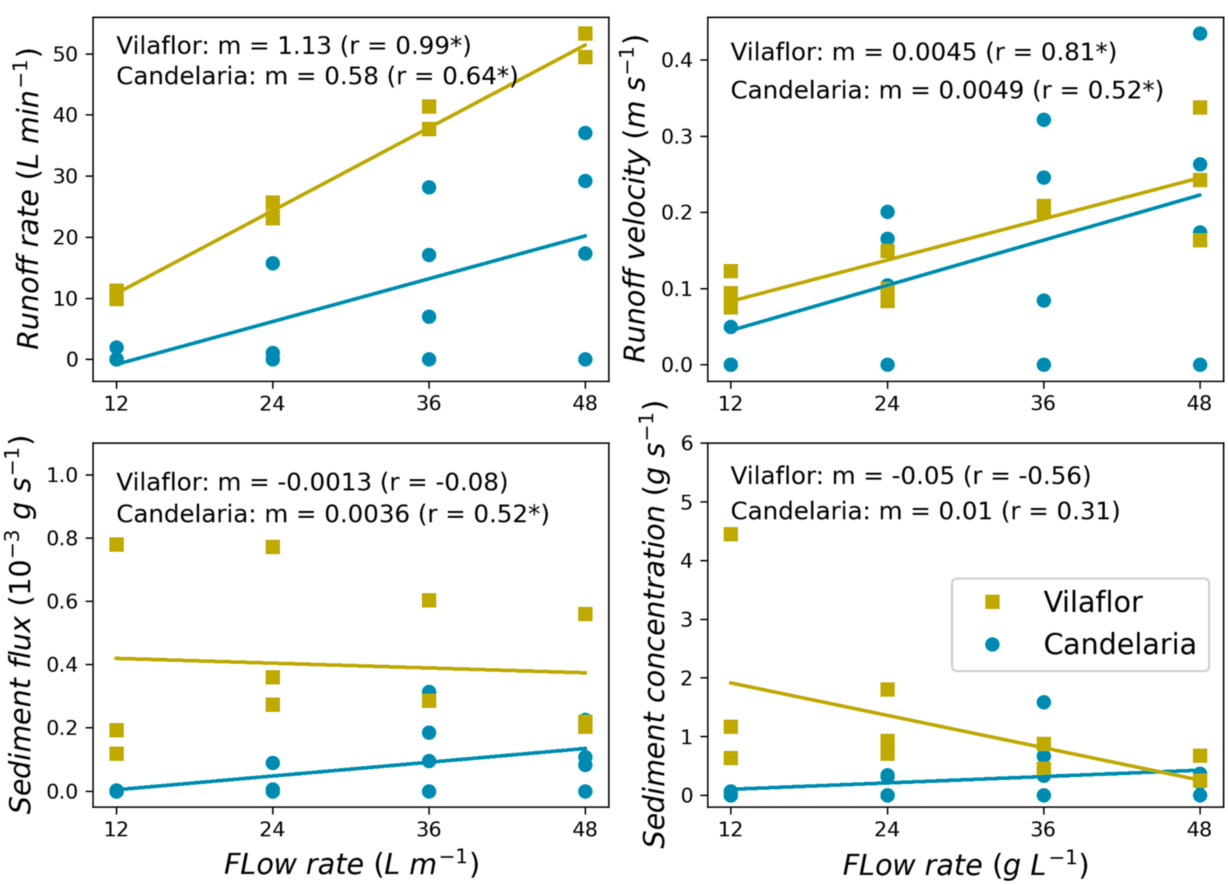

Fig. 5. Relationship between inflow rates and average runoff rate and velocity, and average sediment flux and concentration for the post-wildfire rill plots at the 2015 Candelaria (n = 16) and Vilaflor (n = 24) for the steady state condition (m – slope of the regression equation, r – Pearson's correlation coefficient, * correlation is significant at the 0.05 level).

Table 3
Hillslope erosion monitoring results following the 2015 Vilaflor wildfire including rainfall between cleanouts, characteristics of the event with the highest 10-min maximum intensity (I_{10}) during each monitoring period, average soil loss (coefficient of variation in brackets) and specific soil loss per mm of rainfall for each cleanout period. Annual rainfall, sediment yield and specific soil loss per mm of rainfall for each of the monitoring years are also presented.

Cleanout date (year)	Rainfall between cleanouts (mm)	Maximum I_{10} event Date	Rainfall (mm)	I_{10} (mm h^{-1})	Soil loss (T/ha)	Specific soil loss per mm of rainfall (kg ha^{-1} mm^{-1})
24 Sep 2015 (Installation)						
5 Nov 2015 (1)	137	22 Oct 2015	83	52	1.16 (0.55)	6.6
13 Jan 2016 (1)	12	27 Dec 2015	11	12	0.07 (1.01)	6.2
5 April 2016 (1)	18	30 March 2016	3	5	0.05 (1.14)	2.8
Year 1	**167**				**1.29**	**7.7**
15 Dec 2016 (2)	64	26 Oct 2016	19	17	0.37 (0.55)	5.8
8 March 2017 (2)	84	12 Feb 2017	21	13	0.29 (0.34)	3.4
4 May 2017 (2)	90	28 April 2017	42	35	0.35 (0.47)	3.9
Year 2	**238**				**1.02**	**4.3**
23 Jan 2018 (3)	29	25 Sept 2017	19	41	0.33 (0.43)	11.3
6 April 2018 (3)	163	03 March 2018	42	18	1.12 (0.63)	6.9
Year 3	**192**				**1.45**	**7.5**
15 Jan 2019 (4)	52	25 Oct 2018	11	22	0.18 (0.55)	3.5
Year 4	**52**				**0.18**	**3.5**

Table 4
Hillslope erosion monitoring results following the 2015 Candelaria wildfire including rainfall between cleanouts, characteristics of the event with the highest 10-min maximum intensity (I_{10}) during each monitoring period, average soil loss (coefficient of variation -cv- in brackets) and specific soil loss per mm of rainfall for each cleanout period. Annual rainfall, soil loss and soil loss per mm of rainfall for each of the monitoring years are also presented.

Cleanout date (year)	Rainfall between cleanouts (mm)	Maximum I_{10} event Date	Rainfall (mm)	I_{10} (mm h^{-1})	Soil loss (T/ha)	Specific soil loss per mm of rainfall (kg ha^{-1} mm^{-1})
24 Sep 2015 (installation)						
10 Nov 2015 (1)	378	22 Oct 2015	117	58	1.65 (0.52)	3.8
13 Jan 2016 (1)	41	05 Jan 2016	9	8	0.12 (0.42)	3.0
12 April 2016 (1)	336	20 Feb 2016	87	30	0.21 (0.69)	0.6
Year 1	**755**				**1.98**	**2.6**
13 Dec 2016 (2)	311	05 Nov 2016	41	79	0.27 (0.5)	0.9
5 Jan 2017 (2)	100	18 Feb 2016	61	22	0.09 (1.5)	0.9
8 March 2017 (2)	171	12 Feb 2017	29	23	0.23 (0.9)	1.4
Year 2	**582**				**0.59**	**1.0**
24 Jan 2018 (3)	329	18 Feb 2018	61	22	0.34 (0.20)	1.0
11 April 2018 (3)	368	07 Feb 2018	39	20	0.50 (0.50)	1.4
Year 3	**697**				**0.84**	**1.2**
15 Jan 2019 (4)	610	25 Oct 2018	29	40	0.37 (0.60)	0.6
Year 4	**610**				**0.37**	**0.6**

2013a; Robichaud et al., 2020; Wagenbrenner et al., 2016; Wagenbrenner et al., 2010). Runoff velocity at both Vilaflor and Candelaria was lower than that for weakly weathered ash-cap soils evaluated in the USA despite the greater runoff rate at Vilaflor and steeper terrain at Candelaria (Table 6).

The significantly higher soil loss values obtained at Vilaflor for the rill experiments also showed that the weakly weathered volcanic soils at Vilaflor can be more susceptible to soil erosion than mature volcanic soils at Candelaria after a fire when concentrated flow occurs (Table 2) even though the slope angle at Candelaria was almost 2-fold that at Vilaflor (Table 1). The greater runoff rate and sediment concentrations observed at Vilaflor could have promoted the higher sediment flux rates at this site. Vilaflor showed steady-state sediment flux rate values comparable to those reported for the studies on ash-cap soils in the USA summarised in Table 6. Sediment flux rates at this site were only slightly lower than those reported for *North25* low and high severities, but significantly lower than that for plots 9 m long installed in a high soil burn severity area at *School Fire* site. Robichaud et al. (2010) suggested, however, that longer plots burned at high severity as those at the *School* site produce significantly higher sediment flux rates. Sediment flux rate values at Vilaflor were 2.5-fold that for *Tower* low severity, although rill experiments at the latter fire were conducted 10 months after the fire and, according to Robichaud et al. (2010), similar values to those at *North25* low severity could have been expected at *Tower*. Candelaria showed steady-state sediment flux values one order of magnitude lower than the low burn severity sites at *Tower* and two orders of magnitude lower than high burn severity at *Tower, North25* and both low and high burn severity sites at *School*.

When comparing the rill and flow characteristics obtained here to those reported by others for various soil types and fire severities (Table 6), the combination of wider and deeper rills at Vilaflor exceeded that reported for high severity burned conifer forests (Robichaud et al., 2013a; Robichaud et al., 2020; Wagenbrenner et al., 2016), rangelands at moderate (Pierson et al., 2009) or high severity (Pierson et al., 2008) on granitic soils. Only the studies evaluating fire effects on rangelands produced lower runoff rates than those reported for mature volcanic soils at Candelaria (Pierson et al., 2009; Pierson et al., 2008), whereas weakly weathered volcanic soils at Vilaflor showed greater runoff rate values than those reported by all the previous studies. As for soil loss, the values obtained at Candelaria were between one and two orders of magnitude lower than those reported for other soil, vegetation, and severity combinations. At Vilaflor, sediment flux rate was one order of magnitude lower than that reported by most studies for other soil types and only comparable to those reported by Robichaud et al. (2013a) for the *Terrace Fire* (granite) and by Wagenbrenner et al. (2016) for the *Red Eagle Fire* (argillite) (Table 6).

Table 5
Pearson correlation coefficients (r) between soil loss for the plots at Candelaria (n = 45) and Vilaflor (n = 90) and environmental variables calculated for the cleanout periods. * indicates significant at $p < 0.05$.

		Candelaria		Vilaflor	
		r	p-value	r	p-value
Soil loss (T ha^{-1})	Rainfall (mm)	0.20	0.19	0.71	< 0.001*
	I_{10} (mm h^{-1})	0.23	0.13	0.42	< 0.001*
	Mean I_{10} (mm h^{-1})	0.34	0.02*	0.70	< 0.001*
	Ground cover (%)	−0.06	0.68	−0.06	0.60
	Days after fire	−0.14	0.36	−0.01	0.96
	Year	−0.11	0.47	0.02	0.85
Soil loss per unit rainfall (kg ha^{-1} mm^{-1})	Rainfall (mm)	−0.11	0.47	0.08	0.47
	I_{10} (mm h^{-1})	0.03	0.83	0.38	< 0.001*
	Mean I_{10} (mm h^{-1})	0.29	0.05*	0.08	0.48
	Ground cover (%)	−0.14	0.36	−0.13	0.23
	Days after fire	−0.32	0.03*	0.01	0.96
	Year	−0.29	0.06	0.05	0.65

4.2. Post-fire erosion processes at hillslope scale in volcanic soils

The weakly weathered volcanic soils at Vilaflor were more prone to soil loss than the mature volcanic soils at Candelaria as shown by the higher annual specific soil loss per mm of rainfall for all years (Tables 3 and 4) and the higher soil loss recorded in years 2 and 3 even when precipitation depth was less than half (similar values were found for years 1 and 4). These results match the previously reported different susceptibility to water erosion of mature and weakly weathered volcanic soils (Dahlgren et al., 2004; Poulenard et al., 2001). For the study period, however, the significantly higher precipitation depth at Candelaria can counteract the higher specific soil loss per mm of rainfall of Vilaflor, leading to similar soil loss values over the study period (Table 3 and 4). Neris et al. (2017) reported significantly lower erosion rates in rainfall simulations studies for weakly weathered volcanic soils at Vilaflor than for mature volcanic soils at Candelaria when evaluating interrill erosion processes for the same sites. However, the overall prevalence of rill erosion over interrill erosion in hillslopes where concentrated flow occurs (Lei et al., 1998; Meyer et al., 1975; Mutchler and Young, 1975) are the main reason for the greater values of annual specific soil loss per mm of rainfall at Vilaflor.

The annual soil loss values in the first post-fire year obtained for Vilaflor and Candelaria (Table 7) were comparable to other studies on soils developed on pure volcanic material but with higher annual precipitation depth (Robichaud et al., 2013b; Wagenbrenner et al., 2015) due to the lower specific soil loss per mm of rainfall, a proxy to soil

Table 6
Summary of the results (mean values for the runoff-erosion parameters) reported in the current and previous studies evaluating rill erosion in burned soils with both volcanic and non-volcanic materials. All rill simulations had been conducted in 4 m long plots and within 2 months of the fire unless otherwise noted.

Study	Fire/Site	SBS	Slope	Lithology	Dominant vegetation	Runoff rate	Runoff velocity	Sediment flux rate	Flow depth	Flow width	Comment
			(%)			L min^{-1}	m s^{-1}	kg s^{-1} × 10^{-3}	mm	mm	
Robichaud et al., 2010	Tower	Low	24–52	Colluvium with volcanic ash	Lodgepole pine (*Pinus contorta*)	12	0.07	0.25	6.3	282	10 months after fire
"	North25	Low	27–64	Volcanic ash and pumice	Grand fir (*Abies grandis*)	18	0.24	1	7.1	233	
"	Tower	High	23–75	Colluvium with volcanic ash	Lodgepole pine (*Pinus contorta*)	20	0.29	2.7	7.2	216	10 months after fire
"	North25	High	27–64	Volcanic ash and pumice	Grand fir (*Abies grandis*)	21	0.33	1.1	5.7	247	
Wagenbrenner et al., 2016	School	High	11–46	Weakly weathered basalts with volcanic ash	Douglas-fir (*Pseudotsuga menziesii*)	17.0	0.28	7.2	4.8	453	Plot size 9 m, 12 months after fire
Pierson et al., 2008	Denio	High	30–40	Granite	Sagebrush (*Artemisia tridentata*)	4.7	0.19	3.5	9.7	267	Max flow 15 L min^{-1}
Pierson et al., 2009	Reynolds	Mod-High	35–50	Granite	Sagebrush (*Artemisia tridentata*)	8.5	0.20	5.0	0.7	400	Max flow 21 L min^{-1}
Robichaud et al., 2013a	Terrace	High	39–48	Granite	Douglas-fir (*Pseudotsuga menziesii*)	11	0.17	0.42	5	540	Plot size 9 *m*
Wagenbrenner et al., 2016	Red Eagle	High	11–46	Argillite	Lodgepole pine (*Pinus contorta*)	7.1	0.17	0.9	6	316	Plot size 9 m, 10 months after fire
Robichaud et al., 2020	Hayman	High	17–44	Granite	Ponderosa pine (*Pinus ponderosa*)	18.0	0.26	1.9	5	447	Plot size 9 *m*
Current study	Candelaria	Low-Mod	53–63	Basaltic lava flows	Canarian pine (*Pinus canariensis*)	9.7	0.13	0.07	5.1	250	
"	Vilaflor	Low-Mod	35–47	Phonolite lava flows	"	30.7	0.16	0.61	11.1	610	

Table 7
Summary of the results obtained in other studies evaluating post-fire soil loss at hillslope scale with both volcanic and nonvolcanic parent material in the soil profile. The i_{10} value is for the greatest rainfall event that year.

Study	Fire/Site	Soil Burn Severity	Lithology	Ecosystem	Year 1 P	I_{10}	Soil loss	Specific soil loss per mm of rainfall	Year 2 P	I_{10}	Sediment yield	Specific soil loss per mm of rainfall
					mm	mm h^{-1}	T/ha	kg ha^{-1} mm^{-1}	mm	mm h^{-1}	T/ha	kg ha^{-1} mm^{-1}
Robichaud et al., 2006	Grouse Mtn	High	Volcanic ash and pumice	Subalpine fir (*Abies lasiocarpa*)	1123	29	31.0	27.6	856	17	0.40	0.5
"	Lone Peak	"	"	"	1123	29	16.0	14.2	856	17	0.60	0.7
"	View Point[1]	"	"	"	1123	29	17.0	15.1	856	17	0.90	1.1
Robichaud et al., 2013b	School	High	Weakly weathered basalts with volcanic ash	Douglas-fir (*Pseudotsuga menziesii*)	1483	26	1.33	0.9	1334	35	0.25	0.2
"	Myrtle Creek	"	Granite	"	788	59	3.64	4.6	697	40	0.49	0.7
Wagenbrenner et al., 2015	Tripod	High	Volcanic ash	Ponderosa pine (*Pinus ponderosa*)	371	32	0.17	0.5	315	31	0	0.0
Wagenbrenner et al., 2006	Bobcat		Schists and gneiss	Ponderosa pine (*Pinus ponderosa*)	236[2]	29[3]	9.5	4.0	NA[2]	17[3]	1.2	–
Robichaud et al., 2008	Valley	High	Granite	Grand fir (*Abies grandis*)	724[4]	40	29.0	4.0	927[4]	43	0.8	0.1
Robichaud et al., 2013a	Terrace Mtn	High	Granite	Douglas-fir (*Pseudotsuga menziesii*)	233	47	0.98	4.2	214	13	0.04	0.0
Wagenbrenner et al., 2015	Red Eagle	Mod-high	Argillite	Lodgepole pine (*Pinus contorta*)	1260	28	0.0	0.0	1158	24	0.1	0.1
Robichaud et al., 2013b	Hayman	High	Granite	Ponderosa pine (*Pinus ponderosa*)	316	22	22.6	71.5	329	35	3.60	10.9
"	Hot Creek	"	"	"	1041	38	1.7	1.6	935	26	0.62	0.7
Prats et al., 2012	Pine control	Low	"	Maritime pine (*Pinus pinaster*)	1684	25	0.38	0.2				
"	Eucalyptus	Moderate	"	Eucalyptus plantations (*Eucalyptus globulus*)	1684	25	5.62	3.3				
Prats et al., 2016	Eucalyptus	Moderate	Schists	Maritime pine (*Pinus pinaster*)	1475	31	4.60	3.1	1186	27	0.92	0.8
Malvar et al., 2017		Moderate	Schists	Eucalyptus plantations (*Eucalyptus globulus*)	1423	42	5.13	3.6				
Fernandez et al., 2019		Low-mod	Granite	Atlantic shrublands (*Cystus sp, Erica* sp.)	771.0	30	4.50	5.8	749.0	96.0	0.40	0.5
Fernandez et al., 2011		High	Schists	Gorse (*Ulex europaeus*)	1520.0		35.0	23.0	1194.0		0.70	0.6
Fernandez et al., 2016		High	Granite	Maritime pine (*Pinus pinaster*)	2301.0	17	55.4	24.1				
Current study	Candelaria	Low-Mod	Basaltic lava flows	Canarian pine (*Pinus canariensis*)	755	58	1.98	2.6	582	79	0.59	1.0
"	Vilaflor	Low-Mod	Phonolite lava flows	"	167	52	1.29	7.7	239	35	1.02	4.3

1 – Sediment collected from swales.
2 – Only summer precipitation reported (May – Sep) for year 1. Precipitation data not available for year 2.
3 – I_{10} not reported but estimated according to Arkell and Richards (1986) from the I_{30} reported by Wagenbrenner et al. (2006).

4 – Precipitation data not reported by Robichaud et al. (2008). Values in the table are from a nearby station (Saddle Mountain) for the same period and compiled from https://wcc.sc.egov.usda.gov/nwcc/site?sitenum = 727.

susceptibility to erosion, of the latter. Soil loss values for Vilaflor and Candelaria are an order of magnitude lower than those for soils influenced by silica rich ash and pumice (Robichaud et al., 2006) due to the combination of higher soil susceptibility to erosion and greater annual precipitation depth, mainly when compared to Vilaflor, of the USA sites. Estimations of erosion rates after a torrential rainfall event in weakly weathered volcanic soils also influenced by pumice in Italy (Esposito et al., 2017) were also one order of magnitude higher than that for Vilaflor and Candelaria. Because of the high variability in soil loss rates reported for fire-affected soils on other lithologies, our results ranged from similar to an order of magnitude lower than other published rates (Table 7 and Girona-García et al., 2021), with the greater soil susceptibility to erosion of some non-volcanic soils suggested as being the main driver of major differences.

The low erosion rates at Candelaria when compared to soils with and without volcanic influence affected by low-moderate severity fires can be attributed to the higher infiltration rate, structural stability and resistance to erosion of this mature volcanic soil when compared to weakly weathered volcanic soils (Dahlgren et al., 2004) and other soil types (Nanzyo et al., 1993c; Neris et al., 2013b). This increased stability remained to some extent after the fire according to the burn severity assessment (little impact of fire on soil structure), limiting sediment detachment and transport when compared to other soil types as reported in previous studies evaluating burned volcanic soils (Neris et al., 2017; Poulenard et al., 2001).

As for the weakly weathered volcanic soils at Vilaflor, the armouring of the topsoil with gravels and rocks, covering up to 60 % of the soil surface, reduced interrill erosion when compared to mature volcanic soils at Candelaria (Neris et al., 2017). However, according to the results of this current study, this armouring did not result in further protection of the soil particles and aggregates against detachment and transport by concentrated flow since rill erosion values for Vilaflor are comparable to those reported for fire-affected ash-cap soils and other soil types. The previously reported low structural stability of this weakly weathered volcanic soil at Vilaflor after the same forest fire (Neris et al., 2017) could induce a higher availability of easily-detachable soil particles and aggregates than at Candelaria that can be transported by concentrated flow with a higher transport capacity than laminar flow and splash typical of interrill erosion processes. The erosion rates measured at hillslope scale during the monitoring period reflected the increased susceptibility to rill erosion of weakly weathered volcanic soils at Vilaflor when compared to mature volcanic soils at Candelaria.

4.3. Evolution of hydraulic and erosion parameters with time and flow rate

Sediment flux rate and concentration for the rill experiments decreased considerably with time from the initial to the steady-state condition for both soil types (Fig. 4 and Table 2) even when runoff rate and velocity did not vary significantly or even increased within a rill simulation run. We also observed no change in sediment flux rate and concentration with increasing inflow rates for mature volcanic soils at Candelaria and a significant decrease of these parameters for the last flow rate for weakly weathered soils at Vilaflor even when both runoff rate and velocity increased with inflow increases (Fig. 5). These decreases in soil loss suggest a decrease in soil erodibility, probably due to a drop in the availability of easily detachable and transportable soil particles and aggregates in the rill area. This decrease in soil loss has not been reported for agricultural soils where the supply of loose material is less limited (Elliot et al., 1989), whereas previous studies on rill erosion have also reported sediment exhaustion with time and previous flow event in fire-affected areas (Moffet et al., 2007; Robichaud et al., 2010) and on unpaved forest road surfaces (Foltz et al., 2008).

This sediment depletion process was also observed for mature volcanic soil at Candelaria at hillslope scale at a longer timescale for the study period, but not for weakly weathered volcanic soils at Vilaflor. Soil loss and specific soil loss per mm of rainfall significantly decreased for mature volcanic soil at Candelaria after the first post-fire year (Table 4 and Fig. 3). This response could be related to the soil and vegetation recovery and canopy cover increase but also to the exhaustion of the easily eroded soil particles and aggregates resulting of the impact of fire by previous runoff-erosion events. Other variables affecting the erosion process such as ground cover and rainfall depth and intensity remained stable through the monitoring period. For weakly weathered volcanic soils developed in dry conditions such as those at Vilaflor, the naturally low aggregate stability even in undisturbed condition combined with the limited amount of runoff events provide a larger and longer availability of easily eroded soil particles and, thus, allow for longer periods of constant soil loss.

Previous studies have also reported the transient nature of soil loss after forest fires (Table 7). However, the decrease in soil loss after year 1 reported by previous studies in weakly weathered ash-cap soils and wetter climates than Candelaria and Vilaflor was significantly higher (one to two orders of magnitude) (Robichaud et al., 2013b; Robichaud et al., 2006). Similar severe decreases in soil loss from year 1 to year 2 have been observed in other soil types in wetter areas affected by wildfires in the US (Robichaud et al., 2013a; Robichaud et al., 2013b; Robichaud et al., 2008; Wagenbrenner et al., 2015) and Europe (Fernandez et al., 2019; Fernandez and Vega, 2016; Fernández et al., 2011; Prats et al., 2016b). Only Wagenbrenner et al. (2006) and Olsen et al. (2021) for fire-affected areas with similar annual precipitation to Candelaria and Vilaflor, and Cole et al. (2020) for a wetter climate, reported a slight or no decrease in soil loss from year 1 to year 2. The differences in annual precipitation could be one of the main drivers of this disparate windows of disturbance. Wetter climates not only promote faster ecosystem recovery, with increase in ground and canopy cover and recovery of soil stability affected by the fire, but also usually lead to faster exhaustion of the easily erodible soil particles resulting from the fire impact on the topsoil due to the greater erosivity and frequency of the rain events.

4.4. Wider applicability of the results and implications for modelling

Previous studies on volcanic soils from Vilaflor and Candelaria (Neris et al., 2017) show that hydrologically relevant soil characteristics such as water infiltration rate, bulk density or water retention capacity determined at these sites are comparable to both mature and weakly weathered volcanic soils from the USA (Martin and Moody, 2001; Page-Dumroese et al., 2007), South America (Imeson and Vis, 1982; Morales et al., 2013; Poulenard et al., 2001), Japan (Hiraoka and Onda, 2012; Nanzyo et al., 1993a) or Africa (Biteete-Tukahirwa, 1995). It is therefore suggested that the hydrologic and erosion response of these soil types in the post-fire period can also be representative of similar soils elsewhere. Given the current lack of information for other volcanic areas, they could provide useful approximations for locations elsewhere until local data becomes available.

From a modelling perspective, the results obtained here confirm that volcanic soils have a distinctive hydrologic and erosion response to fire impacts compared to other soil types developed over non-volcanic lithologies and that the degree of weathering of the volcanic material has implications for the runoff-erosion response of the ecosystem. It is therefore necessary to obtain specific erosion parameters for both mature and weakly weathered volcanic soils in order to parameterize runoff-erosion models and produce accurate predictions for this terrain type at larger scales. Additionally, the insights regarding the transient nature of the soil loss and its different temporal evolution for different fire-affected ecosystems should be better evaluated given the critical implications for modelling post-fire erosion they present, since most runoff-erosion models, originally developed for agricultural land, use constant erodibility values (Foltz et al., 2008; Laflen et al., 1997; Morgan and Duzant, 2008; Wischmeier and Smith, 1978).

5. Conclusions

We evaluated the susceptibility to water erosion of two contrasting (weakly weathered vs mature) fire-affected soils developed on volcanic materials using rill experiments and erosion plots. According to the results of this and previous studies, the presence and degree of weathering of the volcanic material appear to be a critical factors in the soil's susceptibility to post-fire water erosion by concentrated flow (rill erosion) and by the combination of sheet wash and rill erosion at hillslope scale (i.e. the combination of interrill and rill erosion). Weakly weathered volcanic soils (i.e those developed on recent tephra deposits or in areas with relatively dry climatic conditions) showed a higher susceptibility to water erosion than mature volcanic soils after fires. When compared to other fire-affected soils with non-volcanic lithologies, mature volcanic soils stand out for their lower susceptibility to rill erosion, irrespective of whether or not volcanic ash was part of the soil profile. In general, burned weakly weathered volcanic soils and burned soils developed on non-volcanic lithologies but with influence of volcanic ash (ash-cap soils) showed similar rill erosion susceptibility, and these soils had lower erosion rates than most of the burned non-volcanic soils previously studied except when ash-cap soils were influenced by pumice.

As for other soil types, most of the erosion occurs during the first rainstorms after the fire and erosion rates usually decline after that. In drier climates and for weakly weathered volcanic soils with low structure stability in undisturbed condition, however, erosion rates can remain elevated for several years since sediment exhaustion is slower due to the naturally large availability of easily erodible soil particles of this soil type and the limited number of runoff and erosion events per year.

From a modelling perspective, the distinctive erosion response of fire-affected mature and weakly weathered volcanic soils when compared to each other and to other soil types suggests that erosion parameters currently available in the literature determined for other non-volcanic soil are not suitable for producing accurate runoff-erosion prediction for these soil types. It is, therefore, necessary to obtain specific rill and interrill erosion parameters for both mature and weakly weathered volcanic soils that, once incorporated into existing runoff-erosion models, will allow for more accurately predicting their contrasting runoff-erosion response.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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