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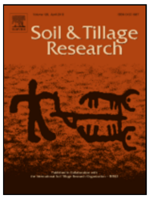

Effectiveness of the application of rice straw mulching strips in reducing runoff and soil loss: Laboratory soil flume experiments under simulated rainfall

João R.C.B. Abrantes[a, *], Sérgio A. Prats[b], J. Jacob Keizer[b], João L.M.P. de Lima[a]

[a] *MARE - Marine and Environmental Sciences Centre, Department of Civil Engineering, Faculty of Sciences and Technology of the University of Coimbra, Coimbra, Portugal*
[b] *CESAM - Centre for Environmental and Maritime Studies, Department of Environment and Planning, University of Aveiro, Aveiro, Portugal*

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ABSTRACT

The use of mulch has a management tool has shown one of the highest effectiveness/cost ratios for improving agricultural soil fertility, crop productivity, soil restoration in badlands and post-fire soil erosion mitigation. Some researchers have suggested that mulching costs can be reduced by applying it in strips rather than over the entire area. However, the implications of strip-wise mulching on the effectiveness to reduce soil erosion are poorly known. This study aimed to evaluate, in laboratory experiments, the effectiveness of strip-wise mulching with rice straw in reducing runoff and soil loss for a highly erodible sandy loam soil at a steep slope of 40%. Six mulching application schemes were compared against a bare soil. The six schemes combined two surface cover rates of 50 and 70% and three spatial patterns: mulch over the entire flume length and two strips of 1/3 and 2/3 of the flume length, both located at the bottom part of the flume. The runoff-erosion experiments involved the simulation of a sequence of three rainfall events, the latter one combining the application of concentrated flow from upslope of the soil flume. Overall, mulching was more effective in reducing soil loss than runoff (50 vs. 25%) and was significantly more effective during the first rainfall event than during the following two events (83 v. 16% for runoff and 92 vs. 53% for soil loss). During the third event, mulching effectiveness dropped significantly with increasing rates of upslope concentrated flow. Overall, mulching was more effective when applied over the entire flume length than over the 1/3 and 2/3 flume's length strips, both in terms of runoff (24 vs. 21 and 13% at 50% soil cover and 41 vs. 33 and 16% at 70% soil cover) and of soil loss (44 vs. 50 and 33% at 50% soil cover and 71 vs. 60 and 39% at 70% soil cover). Even so, these differences were not significant. Therefore, strip-wise mulching can be an effective approach to substantially reduce costs or to maximize the area that can be treated. Its main disadvantage may be that it does not avoid runoff generation and associated transport process in the slope areas where no mulch is applied.

1. Introduction

For a long time, soil and water conservation practices, such as mulching, have been used to improve agricultural soil fertility and crop productivity (Kader et al., 2017) and to promote soil restoration in degraded or vulnerable areas, such as badlands (Bochet and García-Fayos, 2004) and forest lands following wildfire (Bautista et al., 1996). Mulching can improve soil fertility and crop productivity in various manners, such as by increasing water availability through increasing infiltration and reducing evaporation (Adekalu et al., 2007; Montenegro et al., 2013a; Mupangwa et al., 2007), by reducing soil nutrient losses (Qin et al., 2015), by decreasing soil temperature fluctuations (Cook et al., 2006) and by controlling weed infestations (Yordanova and Gerasimova, 2016). In recently burnt areas, mulching has typically been found to be more effective in reducing post-fire erosion than other emergency stabilization measures, such as seeding and construction of log and shrub erosion barriers (Robichaud et al., 2000; Lal, 1976, MacDonald and Larsen, 2009). Furthermore, by reducing mobilization of wildfire ashes and associated transport of pollutants such as metals and PAHs (Campos et al., 2012, 2016) as well as nutrients (Ferreira et al., 2016a,b), mulching can also be expected to reduce the risk of contamination of downstream water bodies.

The effectiveness of mulching in reducing runoff and soil loss can be attributed to three main aspects. Firstly, mulch confers protection to the soil surface against the direct impact of raindrops, reducing splash

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* Corresponding author at: Department of Civil Engineering, Faculty of Sciences and Technology of the University of Coimbra, Rua Luís Reis Santos, Pólo II - Universidade de Coimbra, Coimbra 3030-788, Portugal.

Email address: jrcbrito@msn.com (J.R.C.B. Abrantes)

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erosion and soil detachment and, thereby, limiting the availability of detached soil readily transported by runoff (Gholami et al., 2013) as well as reducing soil surface crusting, sealing and compaction (Cook et al., 2006; Jordán et al., 2010; Montenegro et al., 2013a,b; Zonta et al., 2012). Secondly, mulch increases the hydraulic roughness of the soil surface, thereby reducing surface flow velocity and its transport capacity (Montenegro et al., 2013a,b; Shi et al., 2013). Thirdly, mulch entraps water and soil (Cerdà et al., 2016; Foltz and Wagenbrenner, 2010; Groen and Woods, 2008; Pannkuk and Robichaud, 2003; Prats et al., 2012, 2016b; Robichaud et al., 2013), especially in the beginning of a rainfall event when the mulch is dry and its capacity to retain water and soil particles is highest.

Existing studies have addressed the effectiveness of a wide range of mulch types. This includes a multitude of straw mulches of different species, such as elephant grass (Adekalu et al., 2007), rice (Gholami et al., 2013; Montenegro et al., 2013a,b), wheat (Jordán et al., 2010), soybean (Cook et al., 2006), maize (Mupangwa et al., 2007) and barley (Cerdà et al., 2016), and also other materials such as eucalypt chopped bark (Prats et al., 2012, 2016b), wood strands (Foltz and Wagenbrenner, 2010) and pine needles (Pannkuk and Robichaud, 2003; Hosseini et al., 2017). Surface application of polyacrylamide (Prats et al., 2014) and hydromulch (Prats et al., 2016a) were also studied. All of these studies, however, tested the effectiveness of a single mulch application rate applied in a homogeneous way over the entire area to be treated.

A possible manner to reduce the costs of mulching or, alternatively, to increase the area that can be mulched, is to apply it in a strip or strips covering only a part or parts of the slope rather than over the entire slope. Such strip-wise mulching has been compared with whole-area mulching in burnt as well as unburnt forest areas, in field experiments under natural rainfall conditions (Cawson et al., 2013) and in field experiments of applied concentrated flow from upslope (Harrison et al., 2016). Bhatt and Khera (2006) studied a variety of mulch application schemes (over a whole plot, over the lower one-third of a plot, in horizontal and vertical strips) for reducing agricultural soil loss. Martinez-Raya et al. (2006) compared the erosion reduction effectiveness of different strip schemes of cover crops in agricultural lands. Xu et al. (2017) studied, in laboratory experiments, the reduction of runoff and erosion originated by a cornstalk buffer strip. Are et al. (2011) assessed the impacts of different mulching schemes on the quality of the runoff water as well as on soil nutrient status. Prats et al. (2015, 2017), in a similar laboratory experimental set-up as in the present study, used mulch of forest logging residues to compare the effectiveness of different strip-wise application schemes in reducing runoff and soil loss, under simulated rainfall as well as concentrated flow from upslope. From the above-mentioned studies testing strip-wise mulching of Bhatt and Khera (2006), Cawson et al. (2013), Harrison et al. (2016) and Prats et al. (2015, 2017), it was found that treating the entire plot with mulch resulted in lower runoff and erosion rates than treating parts of the plot only, but that at the same time, these runoff and erosion rates did not differ substantially.

Most studies on the effectiveness of mulching to reduce runoff and erosion were carried out in the field. They involved natural rainfall conditions (Are et al., 2011; Bhatt and Khera, 2006; Cawson et al., 2013; Cook et al., 2006; Martinez-Raya et al., 2006; Mupangwa et al., 2007; Prats et al., 2012, 2014, 2016a,b; Robichaud et al., 2013) as well as simulated rainfall (Cerdà, 1997; Cerdà et al., 2016; Groen and Woods, 2008; Jordán et al., 2010; Mayor et al., 2009; Montenegro et al., 2013b; Robichaud et al., 2013) and applied concentrated flow from upslope (Robichaud et al., 2013; Harrison et al., 2016). Field studies and, in particular, those under natural rainfall conditions, are typically very time-consuming and demanding in resources, as they often require many years to obtain representative results of the targeted soil and rainfall conditions (Lal, 1994). Therefore, laboratory experiments using soil flumes have been widely used to study runoff and soil erosion processes (de Lima et al., 2003, 2013; Marzen et al., 2016; Prats et al., 2018), including to determine the impacts of mulching (Foltz and Wagenbrenner, 2010; Gholami et al., 2013; Montenegro et al., 2013a; Pannkuk and Robichaud, 2003; Prats et al., 2015, 2017; Xu et al., 2017). Arguably, the main advantage of such laboratory experiments is that they allow systematic replication of a wide range of rainfall and terrain conditions (e.g., rainfall spatial and temporal characteristics, surface slope, soil roughness, initial soil moisture content, initial soil water repellency).

As a follow-up study of Prats et al. (2017), this study had as main goal to evaluate the effectiveness of strip-wise mulching the bottom part of the slope with rice straw in reducing runoff and soil loss under laboratory conditions of elevated erosion risk. To this end, a soil flume filled with highly erodible substrate and placed at a steep slope of 40% was subjected to a sequence of three intermittent high-intensity rainfall events, the latter event also involving the upslope application of increasing, strong to extreme concentrated flow rates.

2. Material and methods

2.1. Laboratory setup

The laboratory setup schematized in Fig. 1 was used to study the effectiveness of rice straw mulching strips in reducing runoff and soil loss. The setup comprised, besides a free drainage rectangular soil flume, a rainfall simulator and a water inflow system installed at the

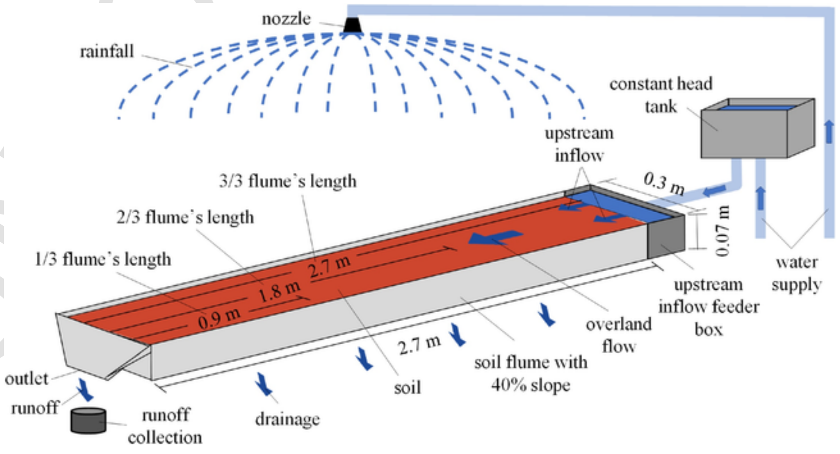

Fig. 1. Schematic representation of the laboratory setup used in the experiments (not to scale).

upper part of the soil flume. Similar setups were used in Abrantes et al. (2017), de Lima and Abrantes (2014a,b), de Lima et al. (2003), Montenegro et al. (2013a,b) and Prats et al. (2015, 2017, 2018).

The flume was placed at a steep slope of 40% and filled with a highly erodible substrate to simulate conditions of elevated erosion risk. Similar conditions can be found in badlands (Cerdà and García-Fayos, 1997), recently burnt hillslopes in the study region (Prats et al., 2012; Martins et al., 2013; Malvar et al., 2016) and marginal agricultural lands (Janeau et al., 2003). The substrate material used in the experiments, characterised as sandy-loam (USDA, 1993), was collected from the left bank of River Mondego in Coimbra, Portugal. Similar substrates, collected from the same region, have been used to study runoff and soil erosion processes in laboratory (de Lima et al., 2003, 2013; Prats et al., 2018), including the effectiveness of mulching (Montenegro et al., 2013a,b; Prats et al., 2015, 2017). Prior to the experiments, the substrate was air-dried, sieved through a 5 mm mesh screen and well-mixed to ensure uniformity and minimize differences between replicates (Lal, 1994).

The rainfall simulator used a steady single downward–oriented full-cone nozzle (1/4-HH-14W FullJet from Spraying Systems Co), with an orifice diameter of 3.6 mm and with an spray angle of 120°, that was positioned at 2.2 m above the geometric centre of the soil flume surface. A submerged pump installed in a constant head reservoir and an electric retention valve allowed a steady operating pressure of approximately 1.4 bar at the nozzle. The rainfall simulator produced rainfall (R) with a mean intensity of $56.9 \pm 2.6\,\mathrm{mm\ h^{-1}}$ (mean ± standard deviation) over the soil flume, with a uniformity coefficient of 85.8 ± 0.7%, calculated according Christiansen (1942) from measurements with 40 rain gauges (plastic cups) spread uniformly over the flume. This rainfall intensity was selected for being similar to the maximum hourly rainfall for a 100-year return period observed in north-central Portugal (Brandão et al., 2001). Raindrops mean diameter and mean velocity, calculated from measurements with a distrometer (Thies Laser Distrometer from Adolf Thies GmbH & Co.), were 0.52 ± 0.21 mm and $1.41 \pm 1.03\,\mathrm{m\ s^{-1}}$, respectively.

A water inflow system, installed at the upper part of the soil flume, was used to simulate upslope concentrated flow, as was applied in the experiments by Robichaud et al. (2013), Harrison et al. (2016) and Prats et al. (2017, 2018). This system consisted of a feeder box and a constant head tank with adjustable height, to allow for distinct rates of water flow onto the flume's soil surface ("inflows"). The system was calibrated in order to deliver three different inflow rates: $1\,F = 0.74 \pm 0.04\,\mathrm{L\,min^{-1}}$, corresponding to $55.0 \pm 2.9\,\mathrm{mm\,h^{-1}}$, $2\,F = 1.54 \pm 0.05\,\mathrm{L\,min^{-1}}$, corresponding to $113.8 \pm 3.6\,\mathrm{mm\,h^{-1}}$; $4\,F = 3.10 \pm 0.09\,\mathrm{L\,min^{-1}}$, corresponding to $229.8 \pm 6.9\,\mathrm{mm\,h^{-1}}$. These strong to extreme inflow rates were selected to explore the limits of the effectiveness of the mulch strips (see Prats et al., 2017).

The organic residues used for mulching consisted of rice straw (*Oryza sativa* L.) from the rice fields in the valleys of the Lower Mondego. The same material had been used by Montenegro et al. (2013a,). Prior to application, the rice straw was air-dried and sieved, excluding the parts smaller than 0.04 m as well as larger than 0.30 m.

2.2. Mulching treatments

Besides the control treatment of bare soil, six mulching treatments with rice straw were tested. These six treatments combined three mulch application schemes with two mulch application rates, as illustrated in Fig. 2. The three application schemes comprised mulching the entire flume and mulching two strips corresponding to the lower 1/3 and the lower 2/3 of the flume. The two application rates provided a straw cover of 50 and 70% within the application area. Therefore, the mulch cover over the entire soil flume was 17, 33, 50, 23, 46 and 70%, respectively, for the six mulch treatments from left to right in Fig. 2b–g.

2.3. Execution of the experiments

At the beginning of each complete experiment, the flume was filled with 82.5 ± 1.7 kg of the air-dried pre-sieved substrate. To this end, the substrate was manually spread over the flume and compacted, to obtain a smooth top surface and a layer with a uniform thickness of approximately 0.062 ± 0.001 m and a bulk density of approximately $1641 \pm 61\,\mathrm{kg\,m^{-3}}$. Substrate samples were collected to perform granulometric analyses (dry sieving for particles larger than 0.05 mm and wet sieving for particles finer than 0.05 mm; LNEC, 1966) and to determine moisture content (after drying at 105 °C for 24 h; ASTM, 2007) as well as organic carbon content (loss on ignition method, i.e. after incineration at 550 °C for 4 h; Hoogsteen et al., 2015). The results of these analyses are given in Table 1.

When mulching treatments were tested, air-dried pre-sieved rice straw was spread uniformly over the soil surface within the area to be mulched. Mulch was then removed or further mulch added, by trial and error, to achieve the targeted cover percentages of 50 or 70%. Percentage cover was estimated as the relative frequency of visual pin-hits at the point-intersections of a 0.04 m mesh grid that was laid out over the plot. This involved 483 pin-hits for the full length of the flume, and proportionally less for the two strips. To achieve the mulch covers of 50 and 70%, application rates corresponded to 63.2 ± 2.0 and $106.8 \pm 2.7\,\mathrm{g\,m^{-2}}$, respectively. Prior to the experiments, mulch sam-

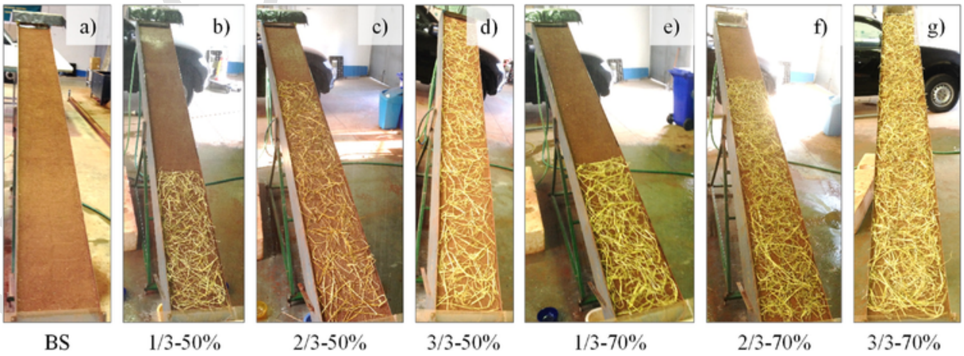

Fig. 2. Photographs of the treatments tested in the experiments: a) Bare soil; b) 1/3 flume's mulch strip with 50% soil cover; c) 2/3 flume's mulch strip with 50% soil cover; d) 3/3 flume's mulch strip with 50% soil cover; e) 1/3 flume's mulch strip with 70% soil cover; f) 2/3 flume's mulch strip with 70% soil cover; and g) 3/3 flume's mulch strip with 70% soil cover. Abbreviations of the different treatments are shown. Differences in colour between photographs are related to differences in the photographic camera, luminosity conditions and time at which photos were taken (i.e. before or during an experimental run).

Table 1
Mean ± standard deviation (s.d.) of the characteristics of the air-dried and pre-sieved sandy-loam substrate and rice straw mulch used in the experiments.

Substrate characteristic	Mean ± s.d.
Gravel (˃2 mm, % weight)	8.6 ± 1.4
Sand (0.05–2 mm, % weight)	82.6 ± 2.4
Silt (0.002–0.05 mm, % weight)	10.7 ± 0.4
Clay (˂0.002 mm, % weight)	0.5 ± 0.1
Median particle size (mm)	0.54 ± 0.01
Moisture (% weight)	0.68 ± 0.01
Organic matter (% weight)	0.86 ± 0.05
Mulch characteristics	Mean ± S.D
Moisture (% weight)	14.83 ± 0.01
Organic matter (% weight)	88.88 ± 0.01
Maximum water retention capacity ($\mathrm{L\,kg^{-1}}$ of dry matter)	3.4 ± 0.3

ples were collected to determine maximum water retention capacity after saturation by sprinkling with the rainfall simulator, moisture content after drying at 105 °C for 24 h, and organic matter content after incineration at 550 °C for 4 h. Table 1 also gives the results of these analyses.

Each complete experiment comprised the simulation of three consecutive events, which were designated as Dry (D), Wet (W) and Wet + inFlow (W + F) runs (Fig. 3). The first two events (Dry and Wet runs) each involved the simulation of rainfall (R) at a rate of $56.9\,\mathrm{mm\,h^{-1}}$ for a duration of 20 min. The first event simulated initially dry soil conditions and the second event, starting 2 h after the end of the first event, simulated initially wet soil conditions. The third event (W + F) equally started 2 h after the end of the second event, simulating initially very wet conditions, and equally lasted 20 min. It involved 20 min of simulated rainfall (R) at the same rate as in the two prior events, and simulation of inflow with increasing rates at 5 min intervals. Therefore, the third events comprised the following sequence of four sub-runs: W + 0F, with $56.9 + 0\,\mathrm{mm\,h^{-1}}$ (R + 0F) till min 5; W + 1F, with $56.9 + 55.0\,\mathrm{mm\,h^{-1}}$ (R + 1F) from min 5 till 10; W + 2F, with $56.9 + 113.8\,\mathrm{mm\,h^{-1}}$ (R + 2F) from min 10 till 15; and W + 4F, with $56.9 + 229.8\,\mathrm{mm\,h^{-1}}$ (R + 4F) from min 15 till 20.

During the experiments, runoff was monitored at the flume's outlet by collecting samples during 10 s for each minute that runoff occurred. The collected samples were analysed for sediment load, following oven drying at 105 °C for 24 h (ASTM, 2007).

After each complete experiment, the remaining substrate and mulch were removed and replaced with new batches of air-dried pre-sieved substrate and mulch, following the above mentioned procedure. This ensured similar initial conditions at the beginning of each complete experiment in terms of surface roughness, bulk density and moisture content.

In total, 24 complete experiments were carried out in this study, six for the bare-soil control treatment and three for each of the six mulching treatments.

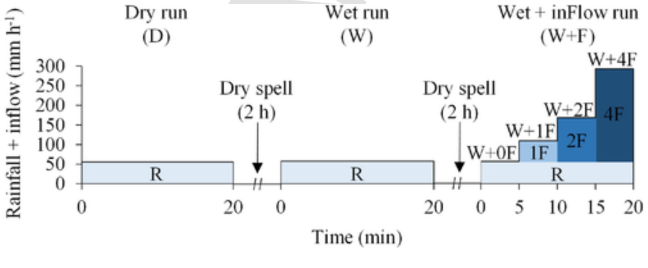

Fig. 3. Rainfall (R) and upslope inflows (1F, 2F and 4F) applied during each complete experiment.

2.4. Statistical analysis

A pair-wise comparison was performed using one-way analysis of variance (one-way ANOVA) with post hoc Tukey-Kramer honestly significant difference (HSD) test to examine if total runoff, total soil loss, runoff coefficient, sediment concentration in runoff, and runoff start time differed significantly between the different six mulching treatments and the bare soil (control treatment). This was done for results of a complete experiment (without considering the results of W + 4F, for reasons explained underneath) and for individual runs and sub-runs, i.e., separately for D, W, W + 0F, W + 1F and W + 2F. One-way ANOVA followed by Tukey-Kramer HSD test was also carried out to determine for each of the seven treatments (control plus six mulching treatments) if runoff coefficient, sediment concentration in runoff and runoff start time differed significantly between the different runs and sub-runs (except W + 4F for the same reasons as before). A two-way ANOVA was performed to test if application scheme (1/3, 2/3 and 3/3 of flume's length) and/or application rate (percentage mulch cover) had a significant impact on total runoff and total soil loss. This was done for each run and sub-run separately (except W + 4F, as before). All statistical analyses were done with IBM SPSS Statistics 22.0 (IBM Corp., 2013), testing significance at α's of 0.05 and 0.01.

3. Results and discussion

The temporal evolution of the average runoff as well as the average soil loss produced in the course of the experiments are presented in Figs. 4 and 5, respectively. The experiments' runoff and soil loss figures are summarized in Table 2. A noteworthy feature of all hydrographs in Fig. 4 is a marked decrease in runoff during the two last sub-runs (W + 2F and W + 4F) of the third event. In both sub-runs, this decrease was due to a strong increase in drainage as a result of rill formation, with rills incising down to the geotextile at the bottom of the layer of substrate filling the flume. This phenomenon is illustrated by the photograph of Fig. 6a. The results of the W + 4F sub-run were excluded from further analysis as rill formation was extreme and the resulting excessive drainage considered to be largely an artefact of the experimental design.

3.1. Runoff

All six mulching treatments reduced total runoff amount for a complete experiment, as shown in Table 2 and Fig. 7. On average, 50 and 70% mulch strips reduced total runoff in 19 and 30% as compared to bare soil conditions. However, such reductions were only significant for the 1/3 and 3/3 mulch strips at 70% soil cover, with figures of 33 and 41%, respectively. Lower runoff reductions were observed for the two 2/3 strip length treatments at 50 and 70%, with figures of 13 and 16%, respectively. The runoff reductions could, at least in part, be attributed to the protection provided by the mulch against the direct impact of raindrops, promoting the dispersion of the kinetic energy of the raindrops, preventing the destruction of soil aggregates and the compaction of the soil surface layer (Gholami et al., 2013). However, the mulch could also have decreased runoff by increasing the hydraulic roughness of the soil surface and by increasing water retention, thereby retarding runoff generation and enhancing infiltration (Cook et al., 2006; Jordán et al., 2010; Montenegro et al., 2013a,b; Zonta et al., 2012; Shi et al., 2013). This was suggested by the fact that the differences in total runoff between mulching and bare soil treatments were more pronounced for the Dry run (first rainfall event on initially dry soil and mulch), with more treatments showing significant reductions, than for the subsequent runs and sub-runs (Table 2). In fact, for the

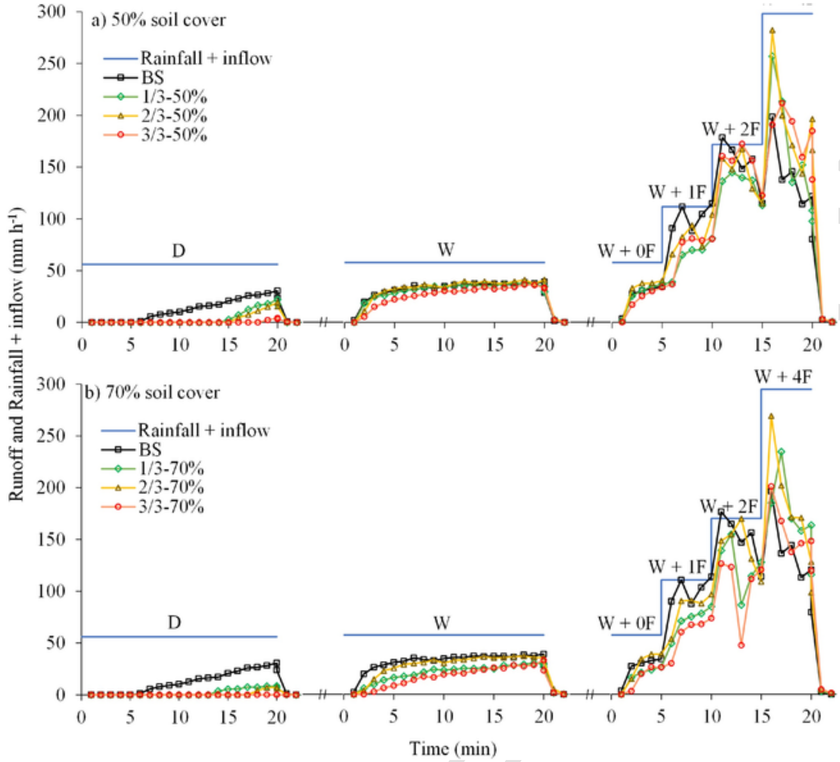

Fig. 4. Runoff hydrographs (average of three repetitions) observed for the bare soil (BS) and the three strip lengths (1/3, 2/3 and 3/3 of flume's length) of rice straw mulch at: a) 50% cover; and b) 70% cover. Rainfall + inflow rates are also shown.

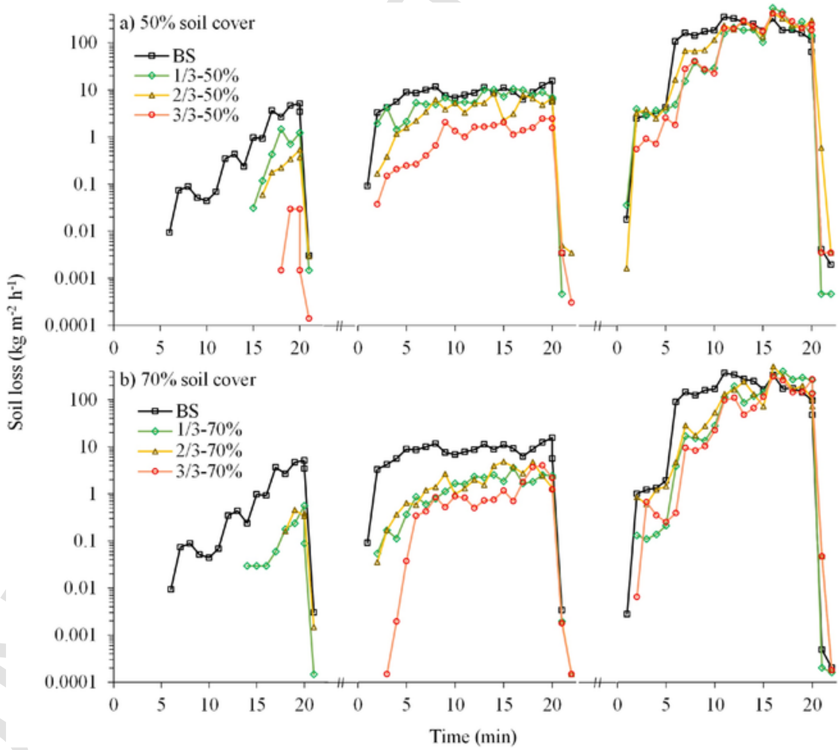

Fig. 5. Soil loss (average of three repetitions) observed for the bare soil (BS) and the three strip lengths (1/3, 2/3 and 3/3 of flume's length) of rice straw mulch at: a) 50% cover; and b) 70% cover. Vertical axis in logarithmic scale (base 10) to better visualisation of results.

Wet run (W) and for the initial 5 min of the Wet + inFlow run (i.e. W + 0F, before inflow took place) runoff slightly increased for the mulch strips of 1/3 and 2/3 at 50% and 2/3 at 70%; however, this increase was not significant.

Average runoff coefficient observed over the consecutive runs and sub-runs (Dry, Wet and Wet + inFlow subdivided in W + 0F, W + 1 F and W + 2F) is shown in Fig. 8 and Table 3. As it can be seen, the hydrological response of the bare soil and six mulching treatments dif-

Table 2
Runoff (mm) and soil loss ($kg\,m^{-2}$) amounts (mean ± standard deviation) observed for all runs and sub-runs and total observed for a complete experiment (except W + 4F). For each run and sub-run, values for mulching treatments in bold ($p < 0.05$) or bold with asterisk ($p < 0.01$) are significantly different from the bare soil according to Tukey-Kramer HSD pair-wise comparison test.

Treatment	D	W	W + 0F	W + 1F	W + 2F	Total
	Runoff (mm)					
Bare soil	4.58 ± 3.09	10.95 ± 1.76	2.08 ± 0.63	8.22 ± 2.12	12.34 ± 1.93	38.17 ± 7.49
1/3–50%	**1.61 ± 0.25**	10.59 ± 0.37	2.09 ± 0.12	**5.24 ± 0.47**	10.81 ± 0.67	30.33 ± 1.30
2/3–50%	1.23 ± 0.65	11.27 ± 0.83	2.42 ± 0.14	6.75 ± 0.26	11.56 ± 0.29	33.22 ± 1.97
3/3–50%	**0.17 ± 0.25**	9.09 ± 0.79	1.71 ± 0.34	5.71 ± 0.61	12.36 ± 1.32	29.06 ± 2.75
1/3–70%	**0.87 ± 1.23**	7.26 ± 2.83	1.42 ± 0.62	5.83 ± 0.51	10.12 ± 0.47	**25.51 ± 4.38**
2/3–70%	0.85 ± 0.60	10.16 ± 1.16	2.21 ± 0.48	6.54 ± 0.59	12.34 ± 0.41	32.10 ± 2.62
3/3–70%	**0 ± 0**	7.6 ± 0.64	1.42 ± 0.10	**5.07 ± 0.46**	**8.33 ± 0.76***	**22.43 ± 0.45***
	Soil loss ($kg\,m^{-2}$)					
Bare soil	0.35 ± 0.23	1.72 ± 0.96	0.17 ± 0.08	7.04 ± 2.91	13.99 ± 1.62	23.27 ± 4.66
1/3–50%	**0.09 ± 0.08**	1.47 ± 0.75	0.17 ± 0.07	**1.25 ± 0.48***	**8.76 ± 1.07***	**11.73 ± 2.14***
2/3–50%	**0.03 ± 0.02**	0.99 ± 0.32	0.16 ± 0.08	**3.56 ± 0.70**	10.84 ± 1.10	**15.57 ± 1.62***
3/3–50%	**0 ± 0**	**0.29 ± 0.07**	0.06 ± 0.05	**1.32 ± 0.83***	11.31 ± 2.38	**12.98 ± 2.44***
1/3–70%	**0.02 ± 0.03**	**0.37 ± 0.18**	0.02 ± 0.01	**1.33 ± 0.74***	**7.62 ± 1.31***	**9.37 ± 0.77***
2/3–70%	**0.03 ± 0.03**	0.63 ± 0.05	0.14 ± 0.10	**2.35 ± 0.98***	11.01 ± 0.82	**14.17 ± 1.77***
3/3–70%	**0 ± 0**	**0.25 ± 0.17**	0.04 ± 0.03	**0.92 ± 0.57***	**5.51 ± 2.35***	**6.73 ± 3.03***

Fig. 6. Photographs of the soil flume: a) Detail of geotextile fabric exposure originated due to extreme erosion; b) Bare soil after W run; c) 1/3–50% after W run; d) Detail of soil deposition on mulch; e) Bare soil at the end of W + F run; f) 1/3–50% at the end of W + F run; g) 2/3–50% at the end of W + F run; and h) 3/3–70% at the end of W + F run. Differences in colour between photographs are related to differences in the photographic camera, luminosity conditions and time at which photos were taken (i.e. during or after an experimental run).

fered between the different runs and sub-runs, indicating the important role of initial soil and mulch moisture contents on runoff (Montenegro et al., 2013a,b; Zonta et al., 2012; Prats et al., 2015, 2017). For bare soil, the average runoff coefficient significantly increased (more than doubled) between the Dry and the Wet and Wet + inFlow runs. This increase in average runoff coefficient was even more significant and larger in the case of the various mulching treatments, ranging from a factor between 4–50 times higher. Overall, for all treatments, no significant differences were observed in runoff between the Wet and the first 5 min of the Wet + inFlow runs (i.e,. W + 0F, before inflow took place).

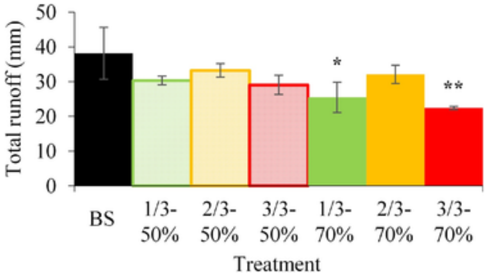

Fig. 7. Total runoff amounts (average and standard deviation bars from three repetitions) observed during a complete experiment. Mulching treatments (1/3, 2/3 and 3/3 of flume's length at 50 and 70% cover) with asterisks ($p < 0.05$) or double asterisks ($p < 0.01$), significantly differ from the bare soil (BS) according to Tukey-Kramer HSD pair-wise comparison test.

However, when inflow started (i.e., W + 1 F), runoff coefficient again increased significantly for all treatments. This increase between W + 0F and W + 1F sub-runs can be explained by the additional inflow, basically doubling the rate of water input (from 56.9 mm h^{-1} in R + 0F to 111.9 mm h^{-1} in R + 1 F). Nonetheless, this increase was more marked under the bare soil (45 to 90%) than under mulching (40 to 60%).

On average, for both the bare soil and mulching treatments, runoff started significantly later during the Dry run (initially dry soil and mulch) than the subsequent Wet and Wet + inFlow runs (initially wet soil and mulch, under or close to saturation), as shown in Fig. 9. Since, in these experiments, runoff was generated mostly by soil saturation, initial soil moisture conditions play a crucial role in the hydrological response (Montenegro et al., 2013a,b; Prats et al., 2015, 2017). Besides this, runoff start time results also show the relevance of mulching (Gholami et al., 2013; Shi et al., 2013). During the Dry run, runoff start time increased significantly from the bare soil (average of 10 min) to the mulching treatments covering 1/3 and 2/3 of the flume's length (average of 17 min). In the case of the mulching treatments covering the entire flume, no runoff occurred during the Dry run (except in one replicate of the 3/3–50% treatment). In case of the Wet and Wet + inFlow runs, runoff started later under bare soil than under mulching, but differed only slightly between the various mulching treatments. Later begin of runoff in mulching treatments occurred because mulching increases the hydraulic roughness of the soil surface, thereby enhancing infiltration and retarding runoff generation. These differences in hydrological timing between bare soil and mulching treatments were also observed with respect to runoff end time. Time between the end of rainfall and the end of runoff was shorter for the bare soil (1–2 min) than for the mulching treatments (1–4 min), because the mulch retains water that, after the end of rainfall, is slowly released which was also observed by Prats et al. (2015, 2017).

3.2. Soil loss

All six mulching treatments significantly reduced soil loss for a complete experiment, as shown in Table 2 and Fig. 10, with an average reduction of 50% in total soil loss as compared to the bare soil. As in the case of runoff, higher soil loss reduction was observed for the mulching treatment covering the entire flume, followed by the 1/3 mulch strip, both at 70% soil cover, with figures of 71 and 60%, respectively. Lower soil loss reductions were observed for the two 2/3 strip length treatments at 50 and 70%, with figures of 33 and 39%, respectively. Like in the case of runoff, a significant reduction in soil loss was observed for the Dry run, amounting to 90 and 95% for the 50 and 70% mulch strips. However, no clear differences were observed in soil loss between the various mulching treatments, except that the reduction in total loss was largest for the two mulching treatments covering the entire soil flume at 50 and 70% cover (99% and 100%, respectively). A significant reduction was also observed for the Wet + inFlow run, after inflow started (i.e., W + 1 F), amounting to 75% for both 50 and 70% mulch strips.

The impacts of mulching on the erosive response are illustrated in Fig. 6. Comparison of Fig. 6b and c illustrates well that mulching reduced and delayed rill formation, in particular by decreasing runoff velocity and its sediment transport capacity (Montenegro et al., 2013a,b; Shi et al., 2013). Also, by protecting the soil surface from the direct impact of raindrops, mulching reduced soil detachment by splash erosion and the amount of soil available for mobilization by runoff (Cerdà et

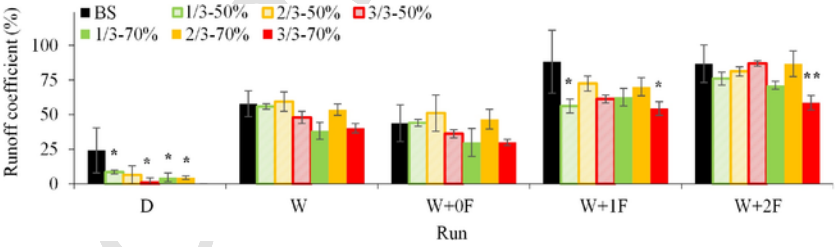

Fig. 8. Runoff coefficient (average and standard deviation bars from three repetitions) observed for all runs and sub-runs. Within each run and sub-run, mulching treatments (1/3, 2/3 and 3/3 of flume's length at 50 and 70% cover) with asterisks ($p < 0.05$) or double asterisks ($p < 0.01$), significantly differ from the bare soil (BS) according to Tukey-Kramer HSD pair-wise comparison test.

Table 3

Mean ± standard deviation of runoff coefficient (%) observed for all runs and sub-runs (except W + 4F). Within the same treatment, values for a run or sub-run, followed by a lowercase letter ($p < 0.05$) or uppercase letter ($p < 0.01$) are significantly different from the run or sub-run corresponding to that letter, according to Tukey-Kramer HSD multiple comparison test. Lowercase letters a, b, c, d and e and uppercase letters A, B, C, D and E correspond to runs D, W, W + 0F, W + 1F and W + 2F, respectively.

Treatment	Runoff coefficient (%)				
	D	W	W + 0F	W + 1F	W + 2F
Bare soil	24.17 ± 16.31bDE	57.79 ± 9.28ad	43.82 ± 13.30DE	88.17 ± 22.73AbC	86.73 ± 13.56AC
1/3–50%	8.48 ± 1.34BCDE	55.85 ± 1.94AcE	44.06 ± 2.48AbdE	56.20 ± 5.01AcE	76.01 ± 4.73ABCD
2/3–50%	6.47 ± 3.44BCDE	59.43 ± 4.38AdE	51.08 ± 2.93ADE	72.45 ± 2.84AbC	81.25 ± 2.01ABC
3/3–50%	0.92 ± 1.30BCDE	47.95 ± 4.15AE	36.18 ± 7.11AdE	61.28 ± 6.53Ace	86.93 ± 9.25ABCD
1/3–70%	4.60 ± 6.51bDE	38.32 ± 14.92ae	29.93 ± 13.10de	62.53 ± 5.46Ac	71.18 ± 3.30Abc
2/3–70%	4.47 ± 3.17BCDE	53.61 ± 6.14AE	46.68 ± 10.11AdE	70.12 ± 6.36Ac	86.78 ± 2.86ABD
3/3–70%	0 ± 0BCDE	40.10 ± 3.40AdE	30.01 ± 2.20ADE	54.42 ± 4.93AbC	58.57 ± 5.32ABC

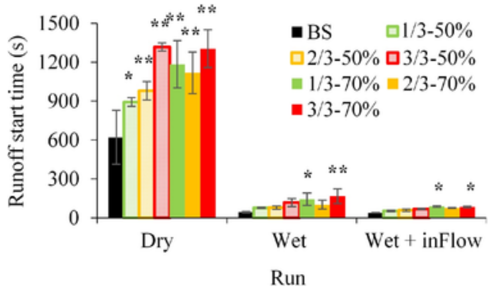

Fig. 9. Runoff start time (average and standard deviation bars from three repetitions) for the Dry, Wet and Wet + inFlow runs. Within each run, mulching treatments (1/3, 2/3 and 3/3 of flume's length at 50 and 70% cover) with asterisks ($p < 0.05$) or double asterisks ($p < 0.01$), significantly differ from the bare soil (BS) according to Tukey-Kramer HSD pair-wise comparison test.

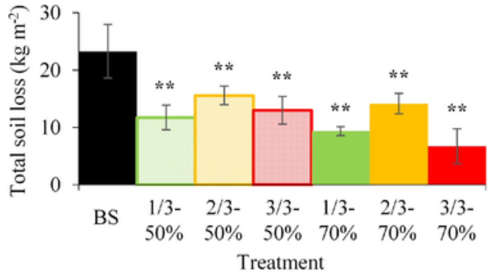

Fig. 10. Total soil loss amounts (average and standard deviation bars from three repetitions) observed during a complete experiment. Mulching treatments (1/3, 2/3 and 3/3 of flume's length at 50 and 70% cover) with asterisks ($p < 0.05$) or double asterisks ($p < 0.01$), significantly differ from the bare soil (BS) according to Tukey-Kramer HSD pair-wise comparison test.

al., 2016; Foltz and Wagenbrenner, 2010; Gholami et al., 2013; Groen and Woods, 2008; Montenegro et al., 2013a,b; Pannkuk and Robichaud, 2003; Prats et al., 2012, 2014, 2015, 2017; Robichaud et al., 2013). Fig. 6d depicts the deposition of sediments within a mulch strip (in this particular case, a 1/3–70% mulch strip), showing that mulch also affects erosion processes by entrapping soil particles transported by runoff. At the same time, however, Fig. 6d illustrates that the capacity of sediment entrapment by the strip is limited, so that the effectiveness of a mulch strip can be expected to decrease with successive erosion events. Fig. 6e–h give an impression of the cumulative impacts of the three different mulch strip lengths (1/3, 2/3 and 3/3 of the flume's length) over the course of the three events (rainfall or rainfall + inflow) of a complete experiment. Clearly, all mulching treatments markedly reduced the extensive rill formation observed under bare soil. At the same time, however, the treatments involving partial mulching of the soil flume revealed a marked contrast between extensive rill formation in the upslope non-mulched part and its absence in the lower mulched part.

The temporal evolution of sediment concentration in runoff during the experiments is presented in Fig. 11. Average sediment concentration observed over the three consecutive runs is shown in Fig. 12 and Table 4. These experiments under controlled conditions clearly demonstrated the importance of initial soil and mulch moisture content on soil loss (Montenegro et al., 2013a,b; Zonta et al., 2012; Prats et al., 2015, 2017). For bare soil, the Wet run produced, on average, five times more total soil loss than the Dry run (1.72 and 0.35 $\mathrm{kg\,m^{-2}}$, respectively) and twice the peak soil loss (13.46 and 6.79 $\mathrm{kg\,m^{-2}\,h^{-1}}$, respectively). For mulching, these differences were even higher, with values of, on average, 21 times for total soil loss (0.65 and 0.03 $\mathrm{kg\,m^{-2}}$) and 11 times for peak soil loss (6.0 and 0.55 $\mathrm{kg\,m^{-2}\,h^{-1}}$). However, these differences were mainly due to differences in runoff response, as, on the contrary to runoff coefficient, differences between the average sediment concentration of the Dry and Wet runs, and also of the first 5 min of the Wet + inFlow runs (i.e., W + 0F, before inflow took place), were never significant. When inflow started (i.e., W + 1 F), both total and peak soil loss, as well as sediment concentration, increased significantly for all treatments. Like in the case of runoff, this increase between W + 0F and W + 1 F sub-runs can be explained by the additional

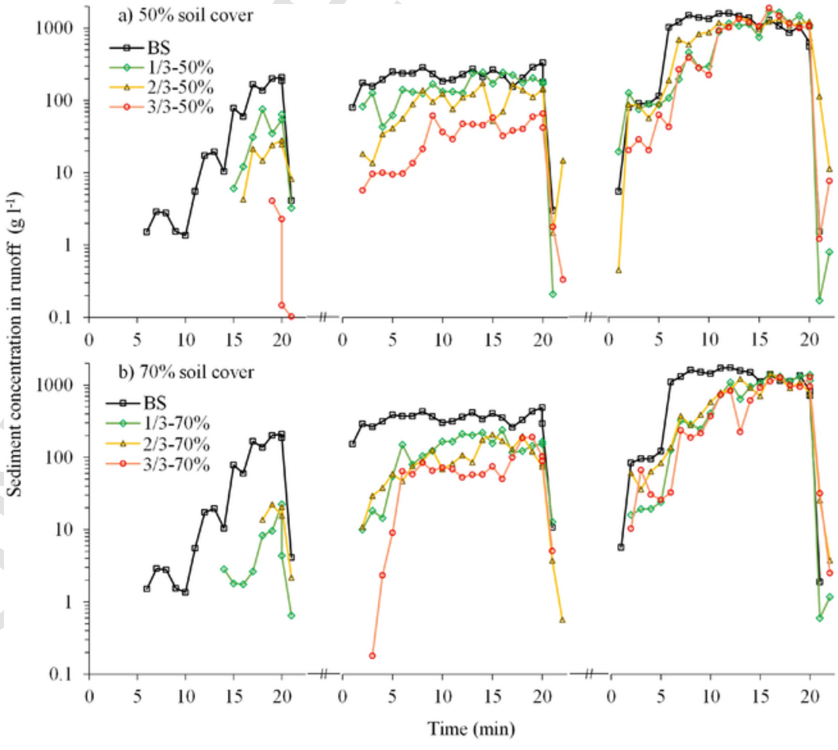

Fig. 11. Sediment concentration in runoff (average of three repetitions) observed for the bare soil (BS) and the three strip lengths (1/3, 2/3 and 3/3 of flume's length) of rice straw mulch at: a) 50% cover; and b) 70% cover. Vertical axis in logarithmic scale (base 10) to better visualisation of results.

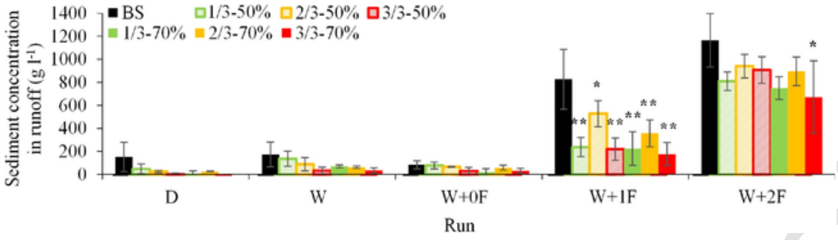

Fig. 12. Sediment concentration (average and standard deviation bars from three repetitions) observed for all runs and sub-runs. Within each run and sub-run, mulching treatments (1/3, 2/3 and 3/3 of flume's length at 50 and 70% cover) with asterisks ($p < 0.05$) or double asterisks ($p < 0.01$), significantly differ from the bare soil (BS) according to Tukey-Kramer HSD pair-wise comparison test.

Table 4

Mean ± standard deviation of sediment concentration in runoff ($g\,l^{-1}$) observed for all runs and sub-runs (except W + 4F). Within the same treatment, values for a run or sub-run, followed by a lowercase letter ($p < 0.05$) or uppercase letter ($p < 0.01$) are significantly different from the run or sub-run corresponding to that letter, according to Tukey-Kramer HSD multiple comparison test. Lowercase letters a, b, c, d and e and uppercase letters A, B, C, D and E correspond to runs D, W, W + 0F, W + 1F and W + 2F, respectively.

Treatment	Sediment concentration in runoff ($g\,l^{-1}$)				
	D	W	W + 0F	W + 1F	W + 2F
Bare soil	151.55 ± 128.19DE	172.55 ± 107.22DE	84.36 ± 35.66DE	826.35 ± 259.44ABCe	1165.21 ± 232.27ABCd
1/3–50%	48.31 ± 42.26E	136.82 ± 65.28E	78.08 ± 29.62E	237.95 ± 83.71E	809.63 ± 80.49ABCD
2/3–50%	24.86 ± 9.9DE	87.69 ± 29.91DE	66.23 ± 31.05DE	527.62 ± 97.1ABCE	940.41 ± 115.28ABCD
3/3–50%	1.96 ± 2.78E	33.25 ± 10.32E	30.46 ± 21.23E	219.88 ± 116.14E	906.91 ± 124.17ABCD
1/3–70%	7.68 ± 10.86E	69.35 ± 57.86E	18.3 ± 3.85E	224.75 ± 113.6E	749.84 ± 103.38ABCD
2/3–70%	26.08 ± 22.47dE	63.42 ± 12.03dE	58.53 ± 32.42dE	356.88 ± 146.89abcE	895.62 ± 98.1ABCD
3/3–70%	0 ± 0E	34.03 ± 22.46e	31.33 ± 21.56e	176.56 ± 100.61e	671.53 ± 315.23Abcd

water input. With the start of the second inflow (2F), during the W + 2F sub-run, sediment concentration, again, increased significantly for all treatments, as opposite to runoff coefficient which remained approximately the same. Overall, all the above mentioned differences in soil loss and sediment concentration between runs were more significant under bare soil than under mulching. Also, they tended to be less significant with increasing amount of mulch applied on the soil flume.

These findings suggest that at the initial stage of a complete experiment, a sediment-limited effect was stronger in the soil loss process, since a significant increase in runoff coefficient between the Dry and Wet runs did not result in a significant increase in sediment concentration. This sediment-limited effect was observed for both bare soil and mulching treatments but was clearer in the last, as a result of the sediment trapping capacity of the mulch. A similar sediment-limited effect was also found in Shi et al. (2013) for straw mulch applications above a threshold of 50% soil cover. Under this value, and also for bare soil, a transport-limited effect was dominant. After the start of the inflow in the W + 1F sub-run, a significant increase in both runoff and sediment concentration was observed for both bare soil and mulching treatments, due to the high increase in water input. With the start of the second inflow in the W + 2F sub-run, a significant increase in sediment concentration was observed for both bare soil and mulching treatments. At this point, runoff did not increase significantly because it was already close to the maximum of 100%. During these rainfall + inflow events, the sediment-limited effect lost importance in the soil loss process, due to the inability of the bare soil to restrain sediments and due to the limited capacity of the mulch to trap sediments. Even so, overall, this increase in sediment concentration was less pronounced in the mulching treatments.

3.3. *Effectiveness of mulching treatments*

The effectiveness of the six mulching treatments in reducing total as well as peak runoff and soil loss is presented in Fig. 13, as percentage of the deviation from the bare soil conditions. Here, the mulching treatments are represented by their overall mulch cover, i.e., the combined cover of the mulch strip and the upper bare soil part (as given in the materials and methods section).

Overall, effectiveness of mulching was more pronounced in the case of soil loss than runoff, in line with the findings of prior studies, both in the laboratory as in the field (Foltz and Wagenbrenner, 2010; Gholami et al., 2013; Groen and Woods, 2008; Montenegro et al., 2013a,b; Pannkuk and Robichaud, 2003; Prats et al., 2012, 2015, 2017; Robichaud et al., 2013; Shi et al., 2013). All six mulching treatments were effective in reducing soil loss for a complete experiment. However, in the case of runoff, only two treatments (1/3–70% and 3/3–70%) were effective in reducing runoff with significant results. Furthermore, effectiveness in this study tended to be higher when mulch cover was 70%, but this was not observed for all simulated rainfall and rainfall + inflow events.

Mulching effectiveness in terms of total and peak runoff (blue lines in Fig. 13a and b, respectively) revealed a distinction between the Dry run and the subsequent Wet and Wet + inFlow runs. In the case of the Dry run, mulching effectiveness was higher and clearly increased with overall mulch cover. In the case of the Wet and Wet + inFlow runs, mulching effectiveness was lower and only slightly decreased with mulch cover (W and W + 0F) or even appeared unrelated with mulch cover (W + 1F and W + 2F). Mulching effectiveness in terms of total and peak soil loss (red lines in Fig. 13a and b, respectively) revealed a clear tendency to be higher for rainfall-only runs and sub-runs (D, W and W + 0F) than when inflow was added (W + 1F and W + 2F). Previous studies simulating series of multiple intermittent rainfall events also found that mulch effectiveness tended to decrease in subsequent events (Prats et al., 2015, 2017; Montenegro et al., 2013a,b; Zonta et al., 2012). The authors attributed this to a decrease in the capacity of the mulch to retain water and sediments. However, positive feedbacks between erosion/deposition processes could also play an important role.

The present laboratory study shows that strip-wise mulching reduced runoff and especially soil loss almost as effectively as mulching of an entire plot. This finding is in agreement with other field (Bhatt and Khera, 2006; Cawson et al., 2013; Harrison et al., 2016; Martinez-Raya et al., 2006) and laboratory studies (Prats et al., 2015, 2017). In a

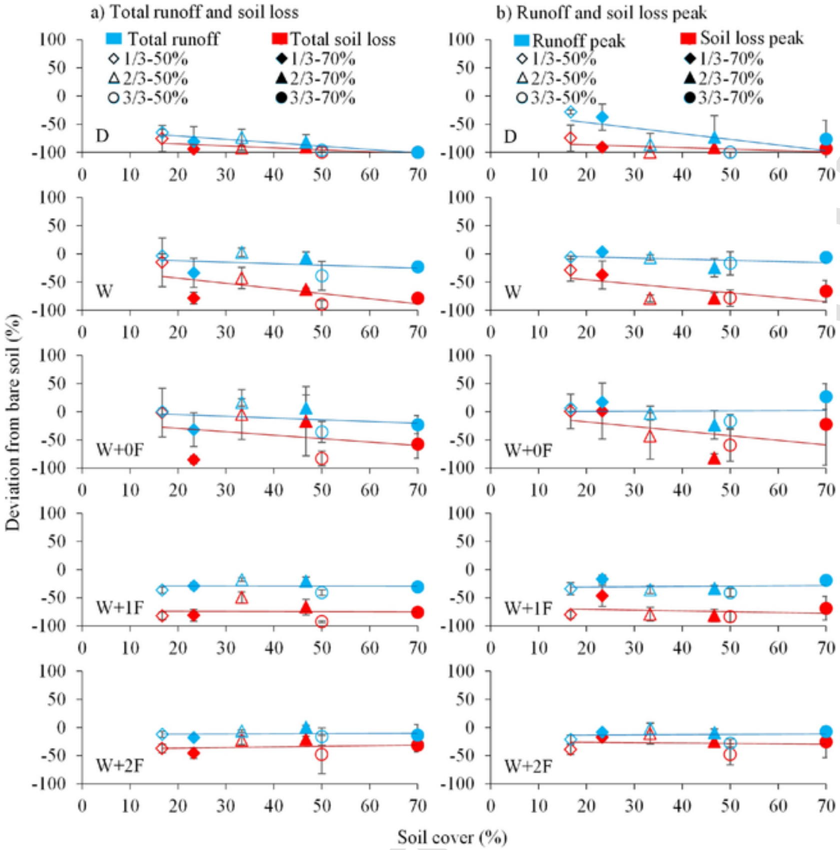

Fig. 13. Effectiveness (average and standard deviation bars from three repetitions) of the six mulching treatments in reducing: a) Total runoff and soil loss; and b) Peak runoff and soil loss. Values are presented as percentage of deviation from the bare soil, as function of overall mulch cover over the entire soil flume (For interpretation of the references to color in the text, the reader is referred to the web version of this article).

field study, Cawson et al. (2013) found that a unburnt strips at the bottom of a prescribed burnt plot were highly effective in reducing soil erosion but less so in reducing runoff. The authors further observed that the strip's effectiveness decreased with increasing rainfall intensity, in line with the decrease in effectiveness reported here between consecutive runs. In another field study, Harrison et al. (2016) found that 1.25 m strip of a 5 m long plot mulched with forest residues reduced soil erosion by 97%, a value that was obtained in this study only by mulching the entire soil flume. Martinez-Raya et al. (2006) found similar reductions with four plant-cover strips of 3 m across their 24 m long plots (97% erosion reduction). Bhatt and Khera (2006) reported a considerably reduction in agricultural soil erosion when mulching their entire 5 m long plot with straw mulch at 600 g m^{-2} (66%) but, in the same experiment, a rather similar effectiveness when mulching just the plot's lower 1.67 m (52%). Prats et al. (2015, 2017) observed that mulching (1/3, 2/3 and 3/3 flume's length) with 70% ground cover significantly reduced soil loss, but not runoff. For the 50% ground cover, only the application over the whole plot was able to reduce soil loss significantly. Sieved forest residue mulch was less effective in reducing runoff (10%) but more effective in reducing erosion (65%), as compared to the straw mulch in this study (25 and 50% runoff and soil loss reduction, respectively). Again, the authors observed that mulching effectiveness decreased with water input. In contrast with the present findings and those of the above-mentioned studies, Are et al. (2011) observed that mulching a single strip was more effective in trapping sediments and associated nutrients than mulching the entire plot, even though the difference was only minor. The authors suggested that this deviant finding could be due to the fact that soil stability on strip-mulched plots was significantly lower than that of the completely-mulched plots, reflecting factors unrelated with the mulching itself. Cerdà (1997) and Mayor et al. (2009) observed that sediment trapping zones created by vegetated patches can reach a limit for sediment storage capacity and, therefore, their effectiveness will decrease over time. Xu et al. (2017) found that a cornstalk buffer strip (1 m wide in a 10 m long soil flume), placed immediately above an initial rill head, more than doubled time to runoff, reduced total runoff in 6% and reduced total soil loss up to 29%. Early application of the buffer strip (i.e., before the first rainfall event) had a larger reduction in soil loss than later application (i.e., after the first rainfall event).

The individual influence of the strip length (1/3, 2/3 and 3/3 of flume's length) and strip cover (50 and 70%) factors in runoff and soil loss is shown in Table 5. For a complete experiment (except W + 4F), both factors had a significant influence on the variations of the hydrologic and erosive responses of the different mulching treatments. In the case of the Dry run, neither the strip length nor the strip cover, individually, played a significant role in the differences in runoff and soil loss of the different mulching treatments, i.e., only the combination of both factors (strip length and cover) had an influence on those differences. In the subsequent Wet and Wet + inFlow runs, either the strip length or the strip cover, individually, played a significant role in runoff and soil loss differences except in the case of soil loss observed in W + 0F. Therefore, the effectiveness of the mulching strips in reducing runoff and soil loss depended, in almost equal proportions, either on the strip length, on the strip cover or on a combination of both factors. Moreover, it should be noticed, that, overall, the strip length factor showed higher values of significance than the strip cover factor. In Prats et al. (2017), variations in the hydrologic response (e.g., runoff, time to runoff, percolation) depended mostly on the strip cover, while varia-

Table 5

F values of the two-way ANOVA to evaluate the individual influence of the strip length (1/3, 2/3 and 3/3 of flume's length) and strip cover (50 and 70%) factors in runoff and soil loss differences between mulching treatments. Test was performed for results of each run and sub-run (D, W, W + 0F, W + 1F and W + 2F) and total observed for a complete experiment (except W + 4F). F values in bold ($p < 0.05$) or bold with asterisk ($p < 0.01$) denote a significant influence.

Strip factor	Runoff					
	D	W	W + 0F	W + 1F	W + 2F	Total
Length (1/3, 2/3 and 3/3)	3.73	3.26	**4.72**	**7.62***	**5.93**	**7.62***
Cover (50 and 70%)	1.36	**6.24**	3.55	0.19	**9.60***	**8.02**
Strip effect	Soil loss					
	D	W	W + 0F	W + 1F	W + 2F	Total
Length (1/3, 2/3 and 3/3)	2.01	**3.92**	2.40	**7.66***	3.47	**6.81**
Cover (50 and 70%)	0.95	**6.12**	2.45	1.44	**5.74**	**7.71**

tions in the erosive response (e.g., soil loss, sediment concentration in runof, rill erosion) depended mostly on the strip length.

4. Conclusions

The main conclusions regarding the soil flume laboratory experiments carried out in this study, considering a sequence of simulated intermittent rainfall events with the addition of an upslope inflow (as concentrated flow), under bare soil and six different rice straw mulching treatments, are:

- The effectiveness of mulching to reduce runoff (25%) was lower than to reduce soil loss (50%). The effectiveness was significantly higher in the first simulated rainfall event, when soil and mulch were initially dry (83% and 92%, respectively) and dropped in the subsequent wet scenarios (16 and 53%, respectively). This drop was mainly attributed to saturation of soil pores, which increased the runoff coefficient and sediment concentration, and to the higher inflow shear stress which strongly increased soil detachment and sediment transport, which exceeded the mulch capacity to retain water and sediments;
- The effectiveness of strip-wise mulching was, in overall terms, lower than that of mulching the entire soil flume. Mulch strips of 1/3 and 2/3 of the flume's length, placed at the bottom part of the slope, reduced runoff in 21 and 13% at a 50% soil cover and 33 and 16% at a 70% soil cover; the corresponding soil loss reductions were 50 and 33% at 50% soil cover and 60 and 39% at 70% soil cover. Mulching the entire flume at 50 and 70% soil covers reduced runoff in 24 and 41% and soil loss in 44 and 71%. Even so, differences tended to become smaller during the successive events, or, in other words, with increasing water input amounts (i.e. cumulative rainfall and increasing upslope inflow rates).

In summary, the present results suggest that the application of mulch in strips at the bottom part of the slope rather than over the entire area can be an effective approach to reduce costs or to maximize the area to be treated, especially if some level of erosion is considered acceptable (e.g., if downslope values at risk are limited) or if mulching material is in short supply. It should be noticed that, strip-wise mulching the bottom part of the slope leaves the upslope untreated area prone to runoff and erosion processes, with negative consequences on site and, possibly, also off-site, at least over the long run.

The present findings would seem to plainly justify follow-up testing under field conditions, both in less sloped intensively-managed agricultural areas with elevated erosion risk and in recently burnt areas. Future work should include alternative strip-wise mulching application schemes, allowing to assess where mulch strips (upper, middle and/or bottom parts of the slope) would be more efficient if mulching the entire slope is not an option (for logistical, cost- and/or time-related reasons). Also, future work should be carried out to verify the advantages and disadvantages of using strip-wise mulching in the context of agricultural soil fertility and crop productivity.

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References

Abrantes, J.R.C.B., de Lima, J.L.M.P., Prats, S.A., Keizer, J.J., 2017. Assessing soil water repellency spatial variability using a thermographic technique: an exploratory study using a small-scale laboratory soil flume. Geoderma 287, 98–104. https://doi.org/10.1016/j.geoderma.2016.08.014.

Adekalu, K.O., Olorunfemi, I.A., Osunbitan, J.A., 2007. Grass mulching effect on infiltration, surface runoff and soil loss of three agricultural soils in Nigeria. Bioresource Technol. 98 (4), 912–917. https://doi.org/10.1016/j.biortech.2006.02.044.

Are, K.S., Babalola, O., Oke, A.O., Oluwatosin, G.A., Adelana, A.O., Ojo, O.A., Oluremi, A., Adeyolanu, O.D., 2011. Conservation strategies for effective management of eroded landform: soil structural quality, nutrient enrichment ratio, and runoff water quality. Soil Sci. 176 (5), 252–263. https://doi.org/10.1097/SS.0b013e3182172b1b.

ASTM, 2007. Standard Test Method for Determination of Water Content of Soil by Direct Heating, ASTM D4959-07. American Society of Testing and Materials International, West Conshohocken, PA, USA, 6 pp..

Bautista, S., Bellot, J., Vallejo, R., 1996. Mulching treatment for postfire soil conservation in a semiarid ecosystem. Arid Soil Res. Rehabil. 10 (3), 235–242. https://doi.org/10.1080/15324989609381438.

Bhatt, R., Khera, K.L., 2006. Effect of tillage and mode of straw mulch application on soil erosion in the submontaneous tract of Punjab, India. Soil Till. Res. 88 (1-2), 107–115. https://doi.org/10.1016/j.still.2005.05.004.

Bochet, E., García-Fayos, P., 2004. Factors controlling vegetation establishment and water erosion on motorway slopes in Valencia, Spain. Restor. Ecol. 12 (2), 166–174. https://doi.org/10.1111/j.1061-2971.2004.0325.x.

Brandão, C., Rodrigues, R., Pinto da Costa, J., 2001. Análise de Fenómenos Extremos: Precipitações Intensas em Portugal Continental. Direção dos Serviços de Recursos Hídricos, Lisbon, Portugal, 64 pp..

Campos, I., Abrantes, N., Keizer, J.J., Vale, C., Pereira, P., 2016. Major and trace elements in soils and ashes of eucalypt and pine forest plantations in Portugal following a wildfire. Sci. Total Environ. 572, 1363–1376. https://doi.org/10.1016/j.scitotenv.2016.01.190.

Campos, I., Abrantes, N., Vidal, T., Bastos, A.C., Gonçalves, F., Keizer, J.J., 2012. Assessment of the toxicity of ash-loaded runoff from a recently burnt eucalypt plantation. Eur. J. For. Res. 131 (6), 1889–1903. https://doi.org/10.1007/s10342-012-0640-7.

Cawson, J.G., Sheridan, G.J., Smith, H.G., Lane, P.N.J., 2013. Effects of fire severity and burn patchiness on hillslope-scale surface runoff, erosion and hydrologic connectivity in a prescribed burn. For. Ecol. Manage. 310, 219–233. https://doi.org/10.1016/j.foreco.2013.08.016.

Cerdà, A., 1997. The effect of patchy distribution of Stipa tenacissima L. on runoff and erosion. J. Arid Environ. 36 (1), 37–51. https://doi.org/10.1006/jare.1995.0198.

Cerdà, A., García-Fayos, P., 1997. The influence of slope angle on sediment, water and seed washoutes on badland landscapes. Geomorphology 18 (2), 77–90. https://doi.org/10.1016/S0169-555X(96)00019-0.

Cerdà, A., González-Pelayo, , Giménez-Morera, A., Jordán, A., Pereira, P., Novara, A., Brevik, E.C., Prosdocimi, M., Mahmoodabadi, M., Keesstra, S., García Orenes, F., Ritsema, C.J., 2016. Use of barley straw residues to avoid high erosion and runoff rates on persimmon plantations in Eastern Spain under low frequency-high magnitude simulated rainfall events. Soil Res. 54 (2), 154–165. https://doi.org/10.1071/SR15092.

Christiansen, J.E., 1942. Irrigation by Sprinkling, California Agricultural Experiment Station Bulletin 670. University of California, Berkeley, CA, USA, 128 pp..

Cook, H.F., Valdes, G.S.B., Lee, H.C., 2006. Mulch effects on rainfall interception, soil physical characteristics and temperature under Zea mays L.. Soil Till. Res. 91, 227–235. https://doi.org/10.1016/j.still.2005.12.007.

de Lima, J.L.M.P., Abrantes, J.R.C.B., 2014. Can infrared thermography be used to estimate soil surface microrelief and rill morphology?. Catena 113, 314–322. https://doi.org/10.1016/j.catena.2013.08.011.

de Lima, J.L.M.P., Abrantes, J.R.C.B., 2014. Using a thermal tracer to estimate overland and rill flow velocities. Earth Surf. Process. Landf. 39 (10), 1293–1300. https://doi.org/10.1002/esp.3523.

de Lima, J.L.M.P., Carvalho, S.C.P., de Lima, M.I.P., 2013. Rainfall simulator experiments on the importance of when rainfall burst occurs during storm events on runoff and soil loss. Zeitschrift für Geomorphologie 57 (1), 91–109. https://doi.org/10.1127/0372-8854/2012/S-00096.

de Lima, J.L.M.P., Singh, V.P., de Lima, M.I.P., 2003. The influence of storm movement on water erosion: storm direction and velocity effects. Catena 52 (1), 39–56. https://doi.org/10.1016/S0341-8162(02)00149-2.

Ferreira, R.V., Serpa, D., Cerqueira, M.A., Keizer, J.J., 2016. Short-time phosphorus losses by overland flow in burnt pine and eucalypt plantations in north-central Portugal: a study at micro-plot scale. Sci. Total Environ. 551–552, 631–639. https://doi.org/10.1016/j.scitotenv.2016.02.036.

Ferreira, R.V., Serpa, D., Machadoa, A.I., Rodríguez-Blanco, M.L., Santos, L.F., Taboada-Castro, M.T., Cerqueira, M.A., Keizer, J.J., 2016. Short-term nitrogen losses by overland flow in a recently burnt forest area in north-central Portugal: a study at micro-plot scale. Sci. Total Environ. 572, 1281–1288. https://doi.org/10.1016/j.scitotenv.2015.12.042.

Foltz, R.B., Wagenbrenner, N.S., 2010. An evaluation of three wood shred blends for post-fire erosion control using indoor simulated rain events on small plots. Catena 80 (2), 86–94. https://doi.org/10.1016/j.catena.2009.09.003.

Gholami, L., Sadeghi, S.H., Homaee, M., 2013. Straw mulching effect on splash erosion, runoff, and sediment yield from eroded plots. Soil Sci. Soc. Am. J. 77 (1), 268–278. https://doi.org/10.2136/sssaj2012.0271.

Groen, A.H., Woods, S.W., 2008. Effectiveness of aerial seeding and straw mulch for reducing post-wildfire erosion, north-western Montana, USA. Int. J. Wildland Fire17 (5), 559–571. https://doi.org/10.1071/WF07062.

Harrison, N.M., Stubblefield, A.P., Varner, J.M., Knapp, E.E., 2016. Finding balance between fire hazard reduction and erosion control in the Lake Tahoe Basin, California–Nevada. For. Ecol. Manage. 360, 40–51. https://doi.org/10.1016/j.foreco.2015.10.030.

Hoogsteen, M.J.J., Lantinga, E.A., Bakker, E.J., Groot, J.C.J., Tittonell, P.A., 2015. Estimating soil organic carbon through loss on ignition: effects of ignition conditions and structural water loss. Eur. J. Soil Sci. 66 (2), 320–328. https://doi.org/10.1111/ejss.12224.

Hosseini, M., Gonzalez Pelayo, O., Vasques, A.R., Ritsema, C., Geissen, V., Keizer, J.J., 2017. The short-term effectiveness of surfactant seed coating and mulching treatment in reducing post-fire runoff and erosion. Geoderma 307, 231–237. https://doi.org/10.1016/j.geoderma.2017.08.008.

IBM Corp, 2013. IBM SPSS Statistics for Windows, Version 22.0. IBM Corp.,, Armonk, NY, USA.

Janeau, J.L., Bricquet, J.P., Planchon, O., Valentin, C., 2003. Soil crusting and infiltration on steep slopes in northern Thailand. Eur. J. Soil Sci. 54 (3), 543–554. https://doi.org/10.1046/j.1365-2389.2003.00494.x.

Jordán, A., Zavala, L.M., Gil, J., 2010. Effects of mulching on soil physical properties and runoff under semi-arid conditions in Southern Spain. Catena 81 (1), 77–85. https://doi.org/10.1016/j.catena.2010.01.007.

Kader, M.A., Senge, M., Mojid, M.A., Ito, K., 2017. Recent advances in mulching materials and methods for modifying soil environment. Soil Till. Res. 168, 155–166. https://doi.org/10.1016/j.still.2017.01.001.

Lal, R., 1976. Soil Erosion Problems on an Alfisol in Western Nigeria and Their Control. International Institute for Tropical Agriculture Monograph No. 1. Communications and Information Office, Ibadan, Nigeria, 160 pp..

Lal, R., 1994. Soil Erosion Research Methods. CRC Press, Boca Raton, Florida, USA, 352 pp..

LNEC, 1966. Solos: Análise Granulométrica, Especificação E196-1966. Laboratório Nacional de Engenharia Civil, Lisbon, Portugal, 9 pp..

MacDonald, L.H., Larsen, I., 2009. Effects of forest fires and post-fire rehabilitation: A Colorado, USA case study. In: Cerdà, A, Robichaud, P.R. (Eds.), Fire Effects on Soils and Restoration Strategies. Science Publishers, Enfield, New Hampshire, USA, pp. 423–452.

Malvar, M.C., Prats, S.A., Keizer, J.J., 2016. Runoff and inter-rill erosion affected by wildfire and pre-fire ploughing in eucalypt plantation of north-central Portugal. Land Degrad. Dev. 27 (5), 1314–1318. https://doi.org/10.1002/ldr.2365.

Martinez-Raya, A., Duran-Zuazo, V.H., Francia-Martinez, J.R., 2006. Soil erosion and runoff response to plant-cover strips on semiarid slopes (SE Spain). Land Degrad. Dev. 17 (1), 1–11. https://doi.org/10.1002/ldr.674.

Martins, M.A.S., Machado, A.I., Serpa, D., Prats, S.A., Faria, S.R., Varela, M.E.T., Gonzalez-Pelayo, O., Keizer, J.J., 2013. Runoff and inter-rill erosion in a Maritime Pine and a eucalypt plantation following wildfire and terracing in north-central Portugal. J. Hydrol. Hydromech. 61 (4), 261–269. https://doi.org/10.2478/johh-2013-0033.

Marzen, M., Iserloh, T., de Lima, J.L.M.P., Ries, J.B., 2016. The effect of rain, wind-driven rain and wind on particle transport under controlled laboratory conditions. Catena 145, 47–55. https://doi.org/10.1016/j.catena.2016.05.018.

Mayor, A.G., Bautista, S., Bellot, J., 2009. Factors and interactions controlling infiltration, runoff, and soil loss at the micro-scale in a patchy Mediterranean semiarid landscape. J. Earth Surf. Process. Landf. 34 (12), 1702–1711. https://doi.org/10.1002/esp.1875.

Montenegro, A.A.A., Abrantes, J.R.C.B., de Lima, J.L.M.P., Singh, V.P., Santos, T.E.M., 2013. Impact of mulching on soil and water dynamics under intermittent simulated rainfall. Catena 109, 139–149. https://doi.org/10.1016/j.catena.2013.03.018.

Montenegro, A.A.A., de Lima, J.L.M.P., Abrantes, J.R.C.B., Santos, T.E.M., 2013. Impact of mulching on soil and water conservation in semiarid catchment: simulated rainfall in the field and in the laboratory. Die Bodenkultur 64 (3-4), 79–85.

Mupangwa, W., Twomlow, S., Walker, S., Hove, L., 2007. Effect of minimum tillage and mulching on maize (Zea mays L.) yield and water content of clayey and sandy soils. Phys. Chem. Earth32 (15–18), 1127–1134. https://doi.org/10.1016/j.pce.2007.07.030.

Pannkuk, C.D., Robichaud, P.R., 2003. Effectiveness of needle cast at reducing erosion after forest fires. Water Resour. Res. 39 (12), 1333. https://doi.org/10.1029/2003WR002318.

Prats, S.A., Abrantes, J.R.C.B., Coelho, C.O.A., Keizer, J.J., de Lima, J.L.M.P., 2018. Comparing topsoil charcoal, ash and stone cover effects on the post-fire hydrologic and erosive response under laboratory conditionsLand Degrad. Dev. https://doi.org/10.1002/ldr.2884.

Prats, S.A., Abrantes, J.R.C.B., Crema, I.P., Keizer, J.J., de Lima, J.L.M.P., 2015. Testing the effectiveness of three forest residue mulch application schemes for reducing post-fire runoff and soil erosion using indoor simulated rain. Flamma 6 (3), 113–116.

Prats, S.A., Abrantes, J.R.C.B., Crema, I.P., Keizer, J.J., de Lima, J.L.M.P., 2017. Runoff and soil erosion mitigation with sieved forest residue mulch strips under controlled laboratory conditions. For. Ecol. Manage. 396, 102–112. https://doi.org/10.1016/j.foreco.2017.04.019.

Prats, S.A., MacDonald, L.H., Monteiro, M.S.V., Ferreira, A.J.D., Coelho, C.O.A., Keizer, J.J., 2012. Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a pine and a eucalypt plantation in north-central Portugal. Geoderma 191, 115–124. https://doi.org/10.1016/j.geoderma.2012.02.009.

Prats, S.A., Malvar, M.C., Vieira, D.C.S., MacDonald, L.H., Keizer, J.J., 2016. Effectiveness of hydromulching to reduce runoff and erosion in a recently burnt Pine plantation in Central Portugal. Land Degrad. Dev. 27 (5), 1319–1333. https://doi.org/10.1002/ldr.2236.

Prats, S.A., Martins, M.A.S., Malvar, M.C., Ben-Hur, M., Keizer, J.J., 2014. Polyacrylamide application versus forest residue mulching for reducing post-fire runoff and soil erosion. Sci. Total Environ. 468–469, 464–474. https://doi.org/10.1016/j.scitotenv.2013.08.066.

Prats, S.A., Wagenbrenner, J., Malvar, M.C., Martins, M.A.S., Keizer, J.J., 2016. Hydrological implications of post-fire mulching across different spatial scales. Land Degrad. Dev. 27 (5), 1440–1452. https://doi.org/10.1002/ldr.2422.

Qin, W., Hu, C., Oenema, O., 2015. Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis. Sci. Rep. 5, 16210. https://doi.org/10.1038/srep16210.

Robichaud, P.R, Jordan, P., Lewis, S.A., Ashmun, L.E., Covert, S.A., Brown, R.E., 2013. Evaluating the effectiveness of wood shred and agricultural straw mulches as a treatment to reduce post-wildfire hillslope erosion in southern British Columbia. Can. Geomorphol. 197, 21–33. https://doi.org/10.1016/j.geomorph.2013.04.024.

Robichaud, P.R., Beyers, J.L., Neary, D.G., 2000. Evaluating the effectiveness of Postfire Rehabilitation treatments. Rocky Mountain Research Station General Technical Report 63. United States Department of Agriculture, Fort Collins, Colorado, USA, 85 pp..

Shi, Z.H., Yue, B.J., Wang, L., Fang, N.F., Wang, D., Wu, F.Z., 2013. Effects of mulch cover rate on interrill erosion processes and the size selectivity of eroded sediment on steep slopes. Soil Sci. Soc. Am. J. 77 (1), 257–267. https://doi.org/10.2136/sssaj2012.0273.

USDA, 1993. Soil Survey Manual, USDA-SCS Handbook 18. U. S. Government Publishing Office, Washington, DC, USA.

Xu, X., Zheng, F., Qin, C., Wu, H., Wilson, G.V., 2017. Impact of cornstalk buffer strip on hillslope soil erosion and its hydrodynamic understanding. Catena 149, 417–425. https://doi.org/10.1016/j.catena.2016.10.016.

Yordanova, M., Gerasimova, N., 2016. Effect of mulching on weed infestation and yield of beetroot (Beta vulgaris ssp. rapaceae atrorubra Krass). Org. Agric. 6 (2), 133–138. https://doi.org/10.1007/s13165-015-0122-6.

Zonta, J.H., Martinez, M.A., Pruski, F.F., Silva, D.D., Santos, M.R., 2012. Effect of successive rainfall with different patterns on soil water infiltration rate. Braz. J. Soil Sci. 36 (2), 377–388. https://doi.org/10.1590/S0100-06832012000200007.