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Effects of length and application rate of rice straw mulch on surface runoff and soil loss under laboratory simulated rainfall

Misagh Parhizkar[a,*], Mahmood Shabanpour[a], Manuel Esteban Lucas-Borja[b], Demetrio Antonio Zema[c], Siyue Li[d], Nobuaki Tanaka[e], Artemio Cerdà[f]

[a] Department of Soil Science, University of Guilan, 41635-1314 Rasht, Iran; misagh.parhizkar@gmail.com; Shabanpour@guilan.ac.ir

[b] Escuela Técnica Superior Ingenieros Agrónomos y Montes, Universidad de Castilla-La Mancha, Campus Universitario, E-02071 Albacete, Spain; manuelesteban.lucas@uclm.es

[c] Department Agraria, Mediterranean University of Reggio Calabria, Loc. Feo di Vito, I-89122 Reggio Calabria, Italy

[d] Research Center for Ecohydrology, Chongqing Institute of Green and Intelligent Technology, Chinese Academy of Sciences, Chongqing 400714, China; syli2006@163.com

[e] Ecohydrology Research Institute, The University of Tokyo Forests, Graduate School of Agricultural and Life Sciences, The University of Tokyo, Seto, Japan; tnk.nobu@gmail.com

[f] Soil Erosion and Degradation Research Group (SEDER), Department of Geography, University of Valencia, Blasco Ibáñez 28, 46001 Valencia, Spain; artemio.cerda@uv.es

* Corresponding author: misagh.parhizkar@gmail.com

Abstract

Forest land affected by deforestation yields high soil and water losses. Suitable management practices need to be found that can reduce these losses and achieve ecological and hydrological sustainability of the deforested areas. Mulch has been found to be effective in reducing soil losses; straw mulch is easy to apply, contributes soil organic matter, and is efficient since the day of application. However, the complex effects of rice straw mulch with different application rates and lengths on surface runoff and soil loss have not been clarified in depth. The current paper evaluates the efficiency of rice straw mulch in reducing the hydrological response of a silty clay loam soil under high intensity and low frequency rainfall events (tap water with total depth of 49 mm and intensity of 98 mm/h) simulated in the laboratory. Surface runoff and soil loss at three lengths of the straw (10, 30, and 200 mm) and three application rates (1, 2, and 3 Mg/ha) were measured in 50 (width) x 100 (length) x 10 (depth) cm plots with disturbed soil samples (aggregate soil size < 4 mm) collected in a deforested area. Bare soil was used as control experiment. Runoff volume and erosion were significantly (at $p < 0.05$) lower in mulched soils compared to control plots. These reductions were ascribed to the water absorption capacity of the rice straw and the protection cover of the mulch layer. The minimum runoff was observed for a mulch layer of 3 Mg/ha of straw with a length of 200 mm. The lowest soil losses were found with straw length of 10 mm. The models developed predict runoff and erosion based on simple linear functions of mulch application rate and length, and can be used for a suitable hydrological management of soil. It is concluded that, thanks to rice straw mulch used as an organic soil conditioner, soil erosion and surface runoff are significantly (at $p < 0.05$) reduced, and the mulch protection contributes to reduce the risk of soil degradation. Further research is, however, needed to analyze the upscaling of the hydrological effects of mulching from the plot to the hillslope scale.

Keywords: Straw mulch; Soil erosion; Mulch application rate; Mulch length; Rainfall simulator.

1. Introduction

Soil erosion is one of the most serious problems impacting the global environment (Zhao et al., 2019). The impacts of soil erosion include land degradation, sedimentation, and nutrient transport, resulting in reduced crop production, decay of soil properties, and poor water quality (Pimentel et al., 1995). Inappropriate soil management practices and land use generally cause these impacts on soils (Lucas-Borja et al., 2019;

Shabanpour et al., 2020), such as the increase of the erosion rates (Cherubin et al., 2017; FAO, 2000).

Sustainable practices to control and mitigate soil erosion are essential worldwide and in particular in the environments that are more prone to erosion risks. For instance, deforestation removes the vegetal cover of woodlands, which usually protect the soil surface from sealing and soil detachment. In the deforested environments, soil is left bare and the lack of vegetation increases runoff and erosion rates.

A possible solution is the use of various types of inorganic mulch (e.g., gravel and other soil particles) and organic mulch (e.g., crop residues) (Patil Shirish et al., 2013; Prats et al., 2017). The term “mulch” refers to those materials - other than soil or living vegetation - that function as a permanent or semi-permanent protective cover over the soil surface (Jordán et al., 2011). Mulch protects the soil against raindrop impact, reduces both the overland flow generation rates and velocity, allows improved infiltration capacity and increases water intake and storage. These beneficial effects of mulch noticeably reduce water and soil loss rates (Prosdocimi et al., 2016b).

The mulch types have variable levels of efficacy in controlling and mitigating soil erosion and even in improving soil properties (de Lima et al., 2019). The increase in the soil organic matter content can be particularly significant when vegetative residues are used as mulch, as shown by García-Orenes et al. (2009) and Jordán et al. (2010). Vegetal mulch types, such as leaf litter, cut-shrub barriers, wood-chips, crop residues, and straw mulch (for instance, with rice or wheat) play, in general, an effective influence on soil erosion rates (de Lima et al., 2019; Fernández et al., 2011; Jordan et al., 2010). For example, in southern Spain Jordán et al. (2010) showed that a wheat straw layer increases rain infiltration and delays runoff generation. In central China Liu et al. (2012) showed that rice straw mulch significantly decreases the sediment yield. Cerdà et al. (2016) showed the positive role of barley straw mulch to reduce the soil erosion in persimmon plantations of eastern Spain. Prosdocimi et al. (2016a) found an immediate reduction in soil losses in vineyards, when straw mulch was applied to soil. However, some negative impacts of vegetal mulch on soil protection capacity have been found in literature. For instance, compared to non-mulched soils, soil mulching with straw or needle casts can increase erosion under heavy rainfall (Rahma et al., 2017; Robichaud et al., 2013a, 2013b).

Rice, along with corn and wheat, is a common staple crop. The total harvested area of rice is 160 x 10^6 ha globally, with most of the 700 x 10^6 t world production grown in Asia (640 x 10^6 t) (IRRI, Africa Rice and CIAT, 2010; Hegde & Hegde, 2013). This makes rice an important source of nutrition for Asia and, in general, worldwide. The vegetal residues of rice cultivation (such as straw) are, therefore, abundant in several countries and are becoming cheaper due to the decreasing demand for it as animal fodder (Omidi-Mirzaee et al., 2017). Therefore, rice straw is a low-cost mulch substrate to protect the soil and improve its fertility (Yadav et al., 2019). Rice straw can improve the hydrological and physico-chemical properties of soil (Obour et al., 2019), thanks to the incorporation into the soil of the ligno-cellulosic substances and the subsequent degradation. Therefore, a practical use of rice straw mulch is beneficial for soil conservation in deforested lands, which, as previously mentioned, are very susceptible to land degradation of ecosystems once they lose the plant cover (Parhizkar et al., 2020). Deforestation due to clear-cutting for timber production induces unsustainable runoff generation and soil erosion rates. Therefore, it is important to evaluate whether soil protection with rice straw mulch can be effective in controlling forest hydrology, and the deforested lands of this country may represent a suitable case study.

In general, the influence of straw mulch on soil hydrology and biochemistry is well documented in many studies worldwide, also for rice straw (Abrantes et al., 2018; Fakhari et al., 2018; Gholami et al., 2013; Prats et al., 2017). However, it is believed there are several factors influencing the effectiveness of straw mulch, including rice variety, straw age and length, as well as application methods, rates, and seasons (Mannering & Meyer, 1963; Pearson et al., 2015). The large number of these influencing factors requires a better comprehension of the effects of rice straw mulch on soil erosion, considering different rice straw characteristics as well as rainfall and soil conditions.

At present, few studies have been done considering the effects of rice straw mulch characteristics on runoff and soil loss (de Lima et al., 2019), particularly for a deforested region. Recently, the latter authors found in a laboratory study that mulch length affected soil loss more than runoff and that erosion decreased with the length of rice straw applied to soil. Despite this isolated study, the need remains for a better comprehension of the effects of rice straw mulch lengths and application rates on erosion of deforested soils at high rainfall intensity. Laboratory studies using rainfall simulators and soil plots under specific rain, soil, and vegetation factors are suggested in order to control the effects of each factor influencing the erosion process (Bombino et al., 2019).

To achieve these goals, the current study evaluates the hydrological effects (surface runoff and soil loss) of three lengths (10, 30, and 200 mm) and three application rates (1, 2, and 3 Mg/ha) of rice straw mulch on deforested soils using a rainfall simulator on soil plots. The soil was sampled in a deforested hillslope of the Saravan Forest Park (Northern Iran). It is hypothesized that the surface runoff and soil loss decrease with higher length and application rate of rice straw. Finally, regression models are proposed to predict runoff volume and soil loss from rice straw lengths and application rates.

The current research should give land managers insight about the most suitable soil application method of rice straw in deforested areas, where the soil erosion rates are high and the need for their reduction is compulsory, to avoid land degradation and other negative environmental impacts.

2. Materials and methods

2.1. Soil sampling, analysis, and characterisation

In Iran, deforestation is one of the most important anthropogenic factors of soil degradation and erosion, especially in the northern part of the country, where deforestation due to illegal logging is one of the major factors causing severe soil erosion (Bahrami et al., 2010; Emadodin, 2008). The soil for the laboratory experiment was selected from a deforested hillslope of the Saravan Forest Park, which is one of the oldest forestlands in Guilan province. The park is located in the south of Rasht city and the outlet coordinates are 37°08′04″ N and 49°39′44″ E (Fig. 1).

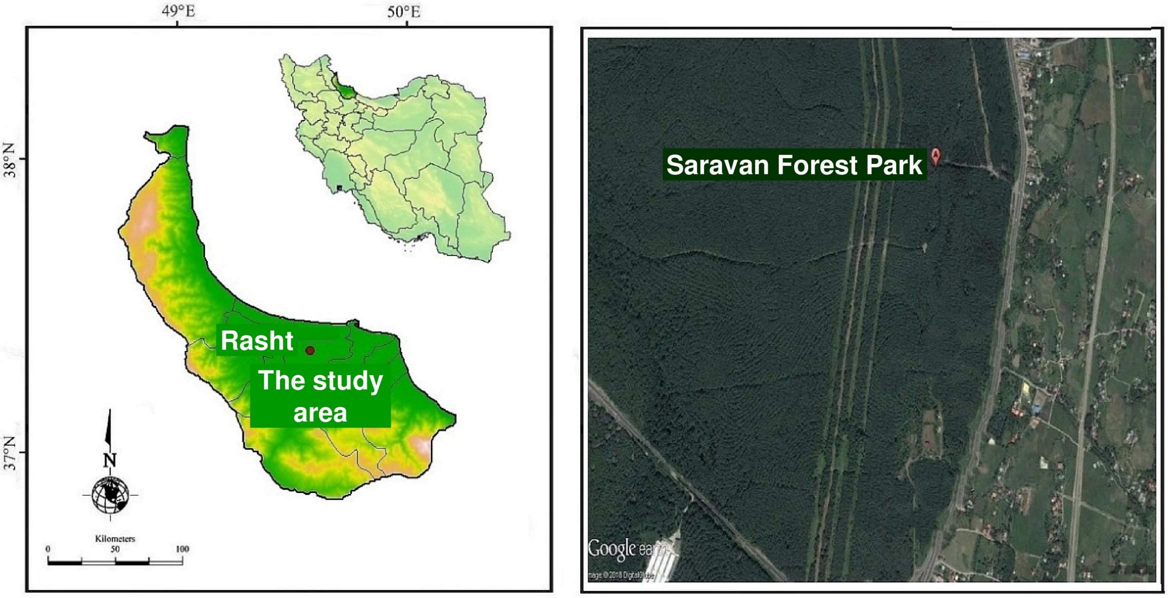

Fig. 1. Geographical location and aerial map (source: Google® Maps®) (Saravan Forest Park, Guilan province, northern Iran).

The Saravan Forest Park is located at a mean altitude 93 m a.s.l. with the slope gradient varying from 12 to 25%. Some hillslopes inside the park, which were deforested to install high-voltage towers one to three years before the investigation, were previously covered by different plant species (trees, shrubs, and herbs) with the highest density among all hillslopes in the park (Parhizkar et al., 2020). The plant biodiversity of the Saravan Forest Park is ample. Some dominant species include *Carpinus betulus*, *Quercus castaneifolia*, *Pinus taeda* and *Parrotia persica*.

According to the Köppen-Geiger classification, the area is characterized by a typical Mediterranean climate, *Csa* type (Kottek et al., 2006). The mean annual temperature and precipitation are 16.3°C and 1360 mm, respectively (IRIMO, 2016).

Soil samples were randomly collected from the top layer (0 to 50 cm) of the deforested hillslope (Kukal & Sarkar, 2010), using the procedure suggested by Singh Sidhu (2015). Before sampling, weeds, rocks, and litter were removed from the soil surface. Then, the soil was transported to the Soil Testing Laboratory of the College of Agriculture, Guilan University. The soil samples were sieved through a 4-mm mesh, to remove the residual gravel and vegetation, and then well mixed. Here, the soil was maintained under a tarpaulin cover until the experiment date, when it was placed in the experimental plots (see section 2.2).

The soil texture was silty clay loam (SDSD, 2017) and the aggregate stability in water, bulk density, and organic matter content of the soil were measured on representative sub-samples of the collected soil samples. Sand, silt, and clay contents of the soils were measured by sieving and hydrometers. Bulk density and aggregate stability were determined using the oven-drying and the wet-sieving methods, respectively. Soil organic matter was estimated using the potassium dichromate colorimetric method.

2.2. Soil characteristics

The mean clay, silt, and sand contents of the studied soil were 37.5 ± 0.02% (where the ± is the standard deviation), 49.9 ± 0.01%, and 12.6 ± 0.01%, respectively. The bulk density was 1487 ± 38 kg/m^3, while the soil aggregate stability, a main indicator of the ability of soil aggregates to resist degradation, was 0.21 ± 0.03. The soil aggregate stability is lower compared to the reference values (0.70-075, Soil Quality Institute, 1998) and those measured by Parhizkar et al. (2020) in the same area (Guilan province, 0.25-0.66), who always reported a large variability of this parameter.

The sampled soil had a mean organic matter content of 1.22 ± 0.05%, which is lower compared the contents (from 2.8 to 3.4%) measured in croplands and gardens in the same area (Guilan province) by Shabanpour et al. (2020), but similar to the values (from 1.28 to 1.87%) reported by Parhizkar et al. (2020) in woodland and forestland of the same park.

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2.3. Plot description

The experimental plots consisted of timber planks (0.5-m wide, and 1-m long with 0.1-m high sides) (Fig. 2a), placed on concrete blocks at a slope of 12% (Shoemaker, 2009; Singh Sidhu, 2015). The base of each plot was made of wood, which was not impervious to water. Small holes were drilled in the base, in order to facilitate water drainage and avoid unrealistic saturation of the soil.

Before the experiments, the soil was air-dried until optimal water content, in order to maintain the stability of soil aggregates (Kukal & Sarkar, 2010). Then, the soil was placed in the plots and the surface was gently leveled by hand. A tarpaulin cover was put on the top, in order to avoid water evaporation from the plot. The plot was equipped with a horizontal collector placed at the downstream side, which conveyed the flows of water and sediment into a plastic tank through a PVC pipe.

2.4. Rainfall simulator

Runoff volume and soil loss were measured between June and July 2019, when rain was simulated on the plot using a hand-crafted simulator (Fig. 2b). The rainfall simulator consisted of two open rectangular boxes, whose bottom was made of a squared grid. The grid was equipped with 70 syringe needles with a diameter of 2.5 mm. The syringe needles, with an outer diameter of 0.7 mm and a length of 40 mm, were uniformly installed 3.1 m above the ground, to provide a rectangular 0.5 m x 1 m spray area. Drop-former rainfall simulators are widely used in the laboratory due to their accuracy.

The rainfall intensity was controlled by feeding the boxes with a flow of tap water (drawn from the municipal aqueduct). This flow was kept constant throughout the experiment via a pipe. Before starting the experiment, the rainfall simulator was calibrated at a rainfall intensity of 98 ± 1.1 mm/h. The experiment was set to this very high value, since extreme weather conditions result in the highest erosion rates in this area. In more detail, the Rasht area has an annual mean rainfall depth of 1353 ± 279 mm with historical (years 1951-2003) extremes of more than 2000 mm (Modarres, 2006; Rahimzadeh et al., 2009). Considering that the climate is typically Mediterranean, where few rainfall events (often two to five) lasting one to two hours account for half of the total precipitation (Modarres, 2006), an intensity of 90-100 mm/h[1] is realistic, and this may result in very erosive precipitations.

The walls of the laboratory prevented wind from disturbing the simulated rain. However, the plots were exposed to a moderate air stream that slightly varied the impact positions of the falling drops. The distribution uniformity of the rainfall intensity (Duke & Perry, 2006) was 83%, a value that can be considered as good in the classification of The Irrigation Association (2002).

2.5. Straw mulch characteristics

The rice variety *Oryza sativa* L. was used for the experimental straw mulch. This variety is considered as one of the most important cultivated rice species in the agricultural fields of northern Iran (Yousefian et al., 2019). Three lengths (10, 30, and 200 mm) of the rice straw mulch were used, as suggested by de Lima et al. (2019). The 200-mm straw length was obtained by breaking the straw particles by hand, whereas the other lengths were produced by shredding (30 mm) and rice grain husking machines (10 mm). A uniform cover of straw mulch was applied over the entire soil surface of the plot for each length (Fig. 2c-e).

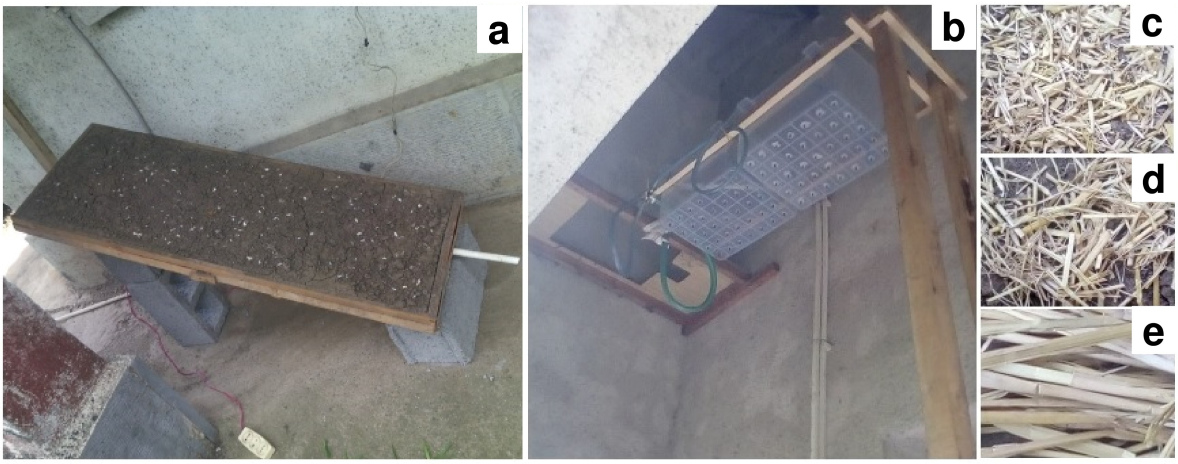

Fig. 2. The experimental plot (a); rainfall simulator (b); 10-mm length rice straw mulch (c); 30-mm length rice straw mulch (d); 200 mm-length rice straw mulch (e), used for the experiment.

A "water absorption capacity" of mulch was estimated on a sample of 100 g of each length (dry weight). This sample was placed on the soil of the plot and a rainfall intensity of 95 mm/h^1 was simulated for 30 min. The water absorption capacity (WAC, %) was:

$$WAC = \frac{w_w - w_d}{w_d} \times 100 \tag{1}$$

where w_w and w_d (g) are the sample weights after and before rainfall, respectively. The wet straw was immediately weighed, in order to limit the water and soil losses.

The estimated values of WAC for 10, 30, and 200-mm lengths of rice straw mulch were 30, 52, and 82%, respectively. Finally, surface cover of soil due to straw mulch application was measured by photographic method followed by image processing using common software.

2.6. The experimental design

Before the tests, the soil was saturated with tap water until ponding. Water was gently and slowly poured on the plot surface to avoid runoff, splashing, and slaking. Then, the soil was left to dry in the open air for 24 hours, to have a water content equal to the field capacity. For each experiment, a 5-10 mm layer of was removed from the plot surface and replaced by a new layer of dry soil, in order to ensure the same content of soil particles. To avoid discontinuities between the old lower and fresh upper layers, the upper surface of the lower layer was roughened using a manual ripper. After preparing the soil with the desired straw mulch application rate and length and filling the rainfall simulator with water, the experiment started, and the runoff volume and soil loss were collected and measured.

An experiment with bare soil in the plot was considered as the “control”. For the other experimental runs, three application rates (1, 2, and 3 Mg/ha) and three lengths (10, 30, and 200 mm) of rice straw mulch were tested (after de Lima et al., 2019). The weight of rice straw mulch for 1, 2, and 3 Mg/ha application rates was 71, 142, and 213 g, respectively. Each test was done in triplicate. Therefore, 30 experiments were done (3 application rates x 3 lengths x 3 replicates + 1 control x 3 replicates). Each experiment was done for 30 min as the runoff discharge was stable in all the experiments by that time (Zhao et al., 2019). After measuring the runoff volume, the collected water was oven-dried at 80°C for 24 h, to measure the sediment weight. Moreover, the runoff outlet time (the time when runoff water starts to drop in the collecting tanks) was measured. This time gives information about the connectivity within the plot.

Hereinafter, each experiment will be indicated as “ARXX-LXXX”, where “ARXX” is related to the mulch application rate and “LXXX” to the mulch length. For instance, AR1-L30 indicated the plots covered by 1 Mg/ha of straw with a length of 30 mm.

2.7. Statistical analysis

Using QQ-normal plots, the normal distribution hypothesis of the samples was checked. An ANalysis Of VAriance (ANOVA) was used to assess the statistical significance of the differences in the runoff volume and soil loss (considered as the dependent variables) among the different straw mulch application rates and lengths (independent variables). Then, a Principal Component Analysis (PCA) was applied, in order to find correlations (using Pearson’s method) among runoff, soil loss, and mulch application rate, length, and cover, as well as to identify the existence of meaningful derivative variables (Principal Components, PCs) (Rodgers & Nicewander, 1988). The correlations between runoff volume and soil loss (dependent variables), and mulch rate and application rate (independent variables) were analyzed by linear multi-regression equations. The simulations were evaluated for “goodness-of-fit” with the corresponding observations. First, observed and simulated values of the water flow were visually compared in scatterplots. Then, the following indicators, commonly used in the hydrological literature (e.g., Legates & McCabe, 1999; Loague & Green, 1991; Willmott, 1982), were applied for a quantitative evaluation: (i) the main statistics (i.e., the maximum, minimum, mean, and standard deviation of both the observed and simulated values); (ii) a set of summary and difference measures, such as the coefficient of determination (R^2), coefficient of efficiency (E), and its modified form (E*, Willmott, 1982), and Root Mean Square Error (RMSE). In particular, E is more sensitive to extreme values, while E* is better suited to significant over- or underprediction by reducing the effect of squared terms. The related equations are reported in Zema et al. (2012), Krause et al. (2005), Moriasi et al. (2007), and Van Liew & Garbrecht (2003).
To summarize:

- R^2 ranges from 0 (no agreement between model and data variance) to 1 (perfect agreement); values over 0.5 are acceptable (Santhi et al., 2001; Van Liew et al., 2003; Vieira et al., 2018);

- E (Nash & Sutcliffe, 1970) and E* are the most common measure of model accuracy and range from −∞ to 1; the model accuracy is “good” if E and E* ≥ 0.75, “satisfactory” if $0.36 \leq$ E and E* ≤ 0.75, and “unsatisfactory” if E and E* ≤ 0.36 (Van Liew & Garbrecht, 2003);
- RMSE, which measures the standard deviation between observations and predictions, should be as close as possible to zero (Fernandez et al., 2010); RMSE is considered good if it predicted value is lower than 0.5 of the observed standard deviation (Singh et al., 2004).

All statistical analyses were done with the SPSS 17.0 and XLSTAT 9.0 software.

3. Results

3.1. Analysis of the hydrological variables

Table 1 lists the volumes and outlet times of runoff as well as the soil losses measured in the experimental plots under the various rice straw mulch lengths and application rates. The control plot produced the highest runoff volume (13.2 ± 0.23 mm), while the lowest value was observed in the AR3-L200 plots (7.62 ± 0.12 mm) (Table 1).

In general, for a given application rate of mulch, the runoff volume decreased and the outlet time increased when the straw length increased. The same trend (decreasing volume and increasing time) can be noticed, if the application rate of mulch increases at the same straw length (Table 1).

This is better explained in Fig. 3a, where it can be noticed that, if the runoff volumes are averaged among the plots with the same mulch length, but different application rates, a significant ($p < 0.05$) decreasing trend for runoff with increasing application rate is evident (11.31 ± 0.10 mm in AR1, to 8.49 ± 0.05 mm in AR3). Conversely, comparing plots with the same mulch application rate, but different lengths, runoff decreased (significantly for the finer straw lengths, $p < 0.05$) when the length increased (from 10.67 ± 0.12 mm in L10 to 9.04 ± 0.06 in L200) (Fig. 3a). The lowest runoff outlet time was found in the control plot (49 s) and the highest in AR3-L200 plots (122 s) (Table 1).

Table 1. Experimental conditions (mulch application rate and length), and surface cover, runoff volume, runoff outlet time, and soil loss evaluated at the plot scale on a deforested soil sampled from the Saravan Forest Park (northern Iran).

Plot	Mulch characteristics		Surface cover (%)	Runoff volume (mm)	Runoff outlet time (s)	Soil loss (Mg/ha)
	Application rate (Mg/ha)	Length (mm)				
BS	0 (bare soil)	-	-	13.20 ± 0.23	49	3.02 ± 0.26
AR1-L10	1	10	38.9 ± 2.1	12.20 ± 0.28	60	1.33 ± 0.10
AR1-L30		30	27.7 ± 1.1	11.52 ± 0.12	68	1.48 ± 0.16
AR1-L200		200	24.6 ± 1.2	10.21 ± 0.10	79	2.28 ± 0.20
AR2-L10	2	10	47.8 ± 5.0	10.39 ± 0.10	84	0.82 ± 0.01
AR2-L30		30	39.9 ± 2.6	9.66 ± 0.08	89	1.11 ± 0.02
AR2-L200		200	30.8 ± 1.3	9.29 ± 0.02	100	1.65 ± 0.12
AR3-L10	3	10	54.8 ± 3.2	9.42 ± 0.05	107	0.42 ± 0.04
AR3-L30		30	48.7 ± 3.8	8.44 ± 0.14	113	0.55 ± 0.02
AR3-L200		200	41.4 ± 4.1	7.62 ± 0.12	122	0.87 ± 0.02

Note: BS = bare soil; in the plot indications (“ARXX-LXXX”), “ARXX” is related to the mulch application rate, and “LXXX” to the mulch length.

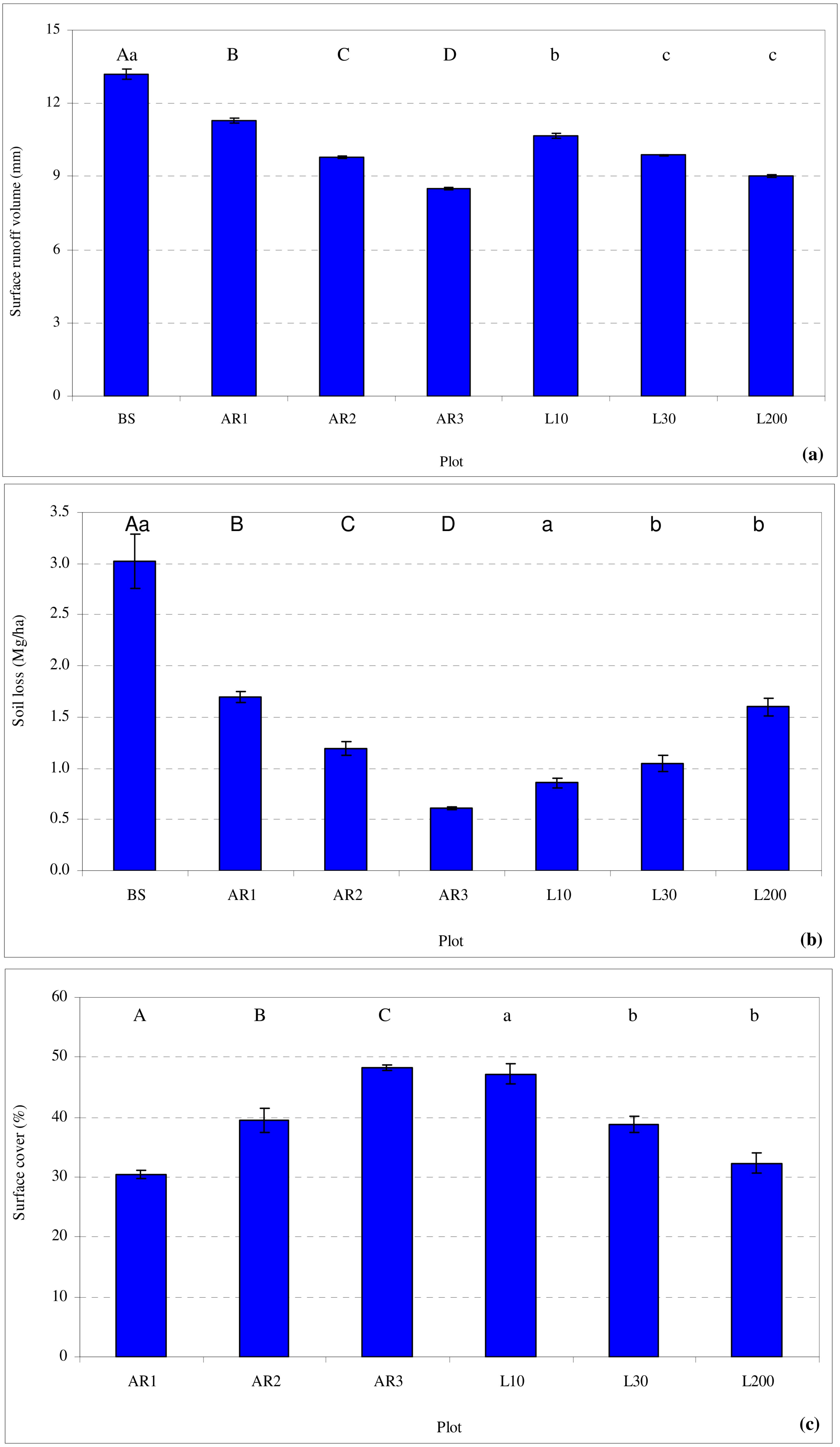
Surface runoff volume (mm)
15
12
9
6
3
0
Aa
B
C
D
b
c
c
BS
AR1
AR2
AR3
L10
L30
L200
Plot
(a)
Soil loss (Mg/ha)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Aa
B
C
D
a
b
b
BS
AR1
AR2
AR3
L10
L30
L200
Plot
(b)
Surface cover (%)
60
50
40
30
20
10
0
A
B
C
a
b
b
AR1
AR2
AR3
L10
L30
L200
Plot
(c)

Fig. 3. Total runoff volume (a), soil loss (b), and surface cover (c) averaged among application rates and lengths of straw mulch applied to a deforested soil and evaluated at the plot scale on a deforested soil sampled from the Saravan Forest Park (northern Iran).

Note: Different lowercase and capital letters indicate significant differences among mulch sizes and doses at p-level < 0.05; BS = bare soil; in the plot indications ("ARXX-LXXX"), "ARXX" is related to the mulch application rate and "LXXX" to the mulch length. The vertical lines on the bars indicate the standard deviations.

Soil erosion was maximum for the bare plot (3.02 ± 0.2 Mg/ha). The lowest erosion was measured in AR3-L10 plots (0.42 ± 0.04 Mg/ha) (Table 2). It is also interesting to note that a high soil loss (2.28 ± 0.20 Mg/ha) was detected in the deforested soil (plots AR1-L200) treated with 1 Mg/ha of 200-mm rice straw, but this value is lower by about 25% compared to the bare soil, showing how mulching with an unsuitable dose and length is still able to significantly reduce soil erosion.

As noticed for the runoff, for a given straw length, the soil loss decreased when the mulch dose increased. Instead, and differently from what observed for runoff, erosion increased if the application rate was kept constant, but the straw length was increased (Table 1). These trends are evident observing Fig. 3b, which shows that, under the same mulch length, soil loss significantly ($p < 0.05$) decreased with increasing mulch rate (from 1.70 ± 0.05 Mg/ha in AR1 to 0.61 ± 0.01 Mg/ha in AR3). Conversely, as the mulch length decreased under a constant application rate, soil loss increased (0.86 ± 0.04 Mg/ha in L10 to 1.60 ± 0.09 Mg/ha in L300), but the differences were significant ($p < 0.05$) only between BS and L10 on one side and L30 and L200 on the other side (Fig. 3b).

Comparing the plots with straw mulch application, the lowest and the highest surface cover were measured in AR1-L200 plots (24.6 ± 1.06%) and AR3-L10 (54.8 ± 3.2%), respectively (Table 1). The variability of surface cover was the opposite of the soil erosion trend among mulch length and application rate, as shown by Fig. 3c, in which the values of surface cover are averaged among the different mulch application rates and lengths. In other words, surface cover increased with the mulch application rate (from 30.4 ± 0.62% in AR1 to 48.3 ± 0.46% in AR3) and decreased with its length (44.5 ± 0.53% in L10 to 32.3 ± 1.69% in L200) under the same length or application rate, respectively. The differences in surface cover were always significant ($p < 0.05$) at different mulch application rates; instead, the length L30 was significantly ($p < 0.05$) different from L10, but not from L200 (Table 1).

3.2. Analysis of relations between the hydrological variables and the mulch parameters

The analysis of Pearson's matrix shows a positive correlation between total runoff on one side, and soil loss ($r = 0.66$) and straw length ($r = 0.91$). Moreover, runoff was negatively correlated with surface cover ($r = - 0.65$) as well as mulch application rate ($r = -0.51$). Soil loss also was negatively correlated surface cover ($r = -0.95$) and mulch application rate ($r = - 0.87$), but not with mulch length ($r = 0.16$) (Table 2).

Table 2. Pearson's correlation matrix among the hydrological variables and mulch characteristics in plots treated with three lengths and three application rates of rice straw mulch applied to a deforested soil sampled from the Saravan Forest Park (northern Iran).

Variables	Mulch application rate	Mulch length	Surface cover	Runoff volume	Soil loss
Mulch application rate	1	0.174	**0.842**	**-0.909**	**-0.872**
Mulch length		1	-0.099	**-0.516**	0.162
Surface cover			1	**-0.649**	**-0.948**
Runoff volume				1	**0.663**
Soil loss					1

Note: Values in bold are significant at *p* level < 0.05.

Two principal components (PCs) were identified using PCA, and explained together 97% of the total variance of the hydrological variables and straw mulch parameters (69% for PC1 and 26% for PC2).

The mulch application rate and surface cover as well as runoff and soil loss had high (absolute value > 0.88) positive and negative loadings, respectively, on PC1, while only mulch length significantly ($p < 0.05$) influenced PC2 (loading over 0.97) (Fig. 4a). In other words, runoff and soil loss were associated with low values of the mulch application rate and surface cover (Fig. 4b).

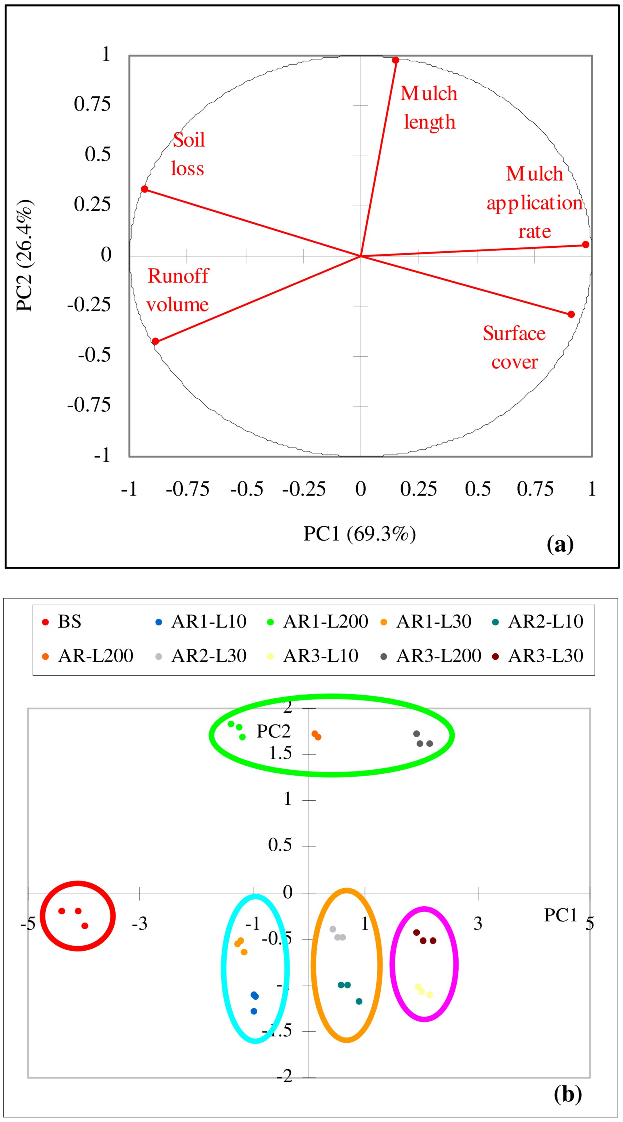

Fig. 4. Loadings of the original hydrological variables and straw mulch characteristics (length, application rate, and surface cover) (PC_1 and PC_2) (a) and scores on the first two Principal Components provided by PCA applied to plots (b) with deforested soils sampled from the Saravan Forest Park (northern Iran).

Note: BS = bare soil; in the plot indications (“ARXX-LXXX”), “ARXX” is related to the mulch application rate and “LXXX” to the mulch length.

Plotting the hydrological variables and the associated mulch parameters on the two PCs, five well differentiated clusters were evident: a first cluster grouping the control plots (associated with low values of PC1), a second group with AR1-L200, AR2-L200 and AR3-L200 plots, associated with high values of PC2) and four other clusters with the remaining plots, characterized by intermediate values of PC1 and low values of PC2 (Fig. 4b).

3.3. Modeling runoff volume and soil loss using mulch parameters

Table 3 lists the coefficients of the equations estimating runoff volume and soil loss from mulch application rate and length.

Table 3. Coefficients of the multi-regression equations between runoff volume or soil loss and straw mulch parameters (application rate, [Mg/ha]), and length, [mm]) in plots treated with different lengths and application rates of straw mulch applied to a deforested soil sampled from the Saravan Forest Park (northern Iran).

Model parameter	Runoff volume	Soil loss
Intercept	13.275	2.506
Mulch application rate	-1.429	-0.760
Mulch length	-0.008	0.002
Mulch application rate x length	0.001	0.001

The proposed equations are the following:

$$RV = -1.429\ MAR - 0.008\ ML + 0.001\ ML \cdot MAR + 13.275 \qquad (2)$$

$$SL = -0.760\,MAR + 0.002\,ML + 0.001\,ML \cdot MAR + 2.506 \qquad (3)$$

where RV = surface runoff volume (mm), SL = soil loss (Mg/ha), MAR = mulch application rate (Mg/ha), and ML = mulch length (mm).

The explanatory capacity of these equations was very high for both the modeled hydrological variables (R^2 equal to 0.96 for surface runoff and 0.87 for soil loss). The predictions of both surface runoff and soil loss were very close to the line of perfect agreement (Fig. 5).

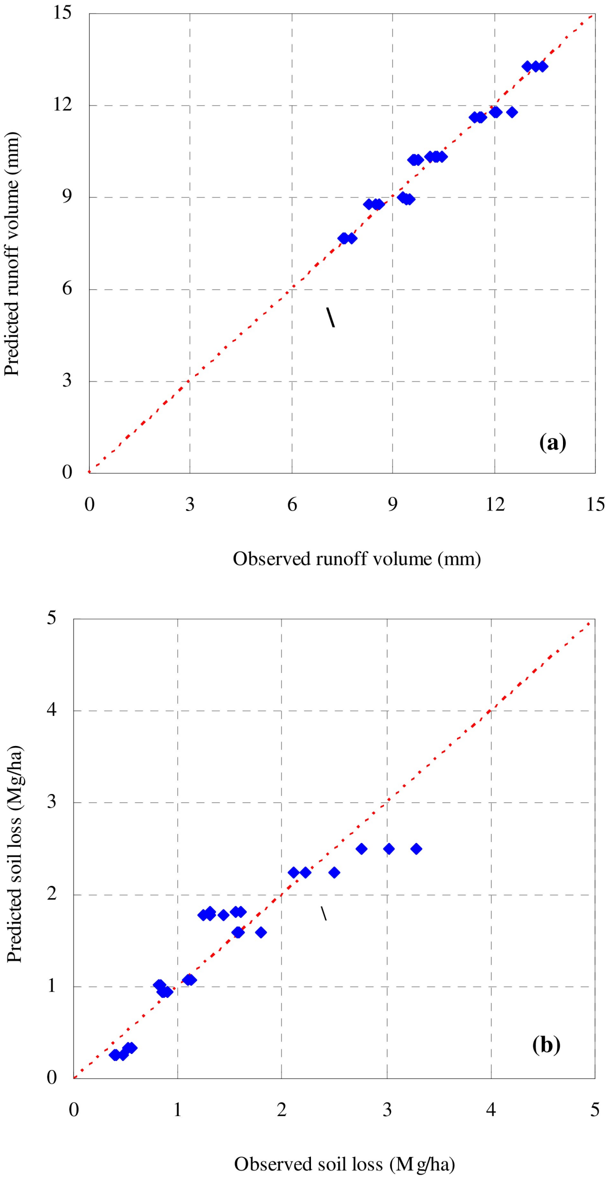

Fig. 5. Scatterplots of runoff volume (a) or soil loss (b) observed and predicted using the multiregression models based on rice straw mulch parameters (application rate and length) in plots with a deforested soil sampled from the Saravan Forest Park (northern Iran).

Not only are the statistics of the observed and predicted variables very close (maximum difference of 33.5% for the maximum values of soil loss), but also the indexes gave values exceeding the acceptance limits suggested by the literature (Santhi et al., 2001; Singh et al., 2004; Van Liew et al., 2003; Vieira et al., 2018; Van Liew & Garbrecht, 2003). In more detail, E was good for runoff and soil loss (0.96 and 0.87, respectively), while E* was good for runoff (0.80) and satisfactory (0.65) for soil loss. The values of RMSE were always lower than 50% of the observed standard deviations (Table 4).

Table 4. Values of the criteria adopted for evaluating the accuracy of equations (2) and (3) to predict the soil loss and runoff volume from mulch parameters in plots treated with different lengths and application rates of straw mulch applied to deforested soils sampled from the Saravan Forest Park (northern Iran).

Hydrological variable		Statistic				Index			
		Mean	Min	Max	Std. Dev.	R^2	E	E*	RMSE
Runoff volume	Observed	10.2	7.5	13.4	1.7	0.96	0.96	0.80	0.33
	Predicted	10.2	7.7	13.3	1.6				
Soil loss	Observed	1.35	0.39	3.29	0.78	0.87	0.87	0.65	0.28
	Predicted	1.35	0.26	2.51	0.73				

Note: Min = minimum; Max = maximum; Std. Dev. = Standard Deviation; R^2 = coefficient of determination; E and E* = coefficients of efficiency of Nash and Sutcliffe (1970) in the original (E) and modified (E*) form; and RMSE = root mean square error (expressed in mm for runoff volume and Mg/ha for soil loss).

4. Discussion

4.1. The influence of mulching conditions on runoff volume and soil loss

Previous studies have evaluated how much straw influences the hydrological response of the soil under different experimental conditions (e.g., de Lima et al., 2019; Gholami et al., 2013, 2014; Keesstra et al., 2019; Lucas-Borja et al., 2018; Sadeghi et al., 2015). However, the research done in the field is highly affected by other factors, such as the rainfall intensity, spatial variability of soil properties, plant cover, and soil moisture. In the current study, the straw mulch cover has been isolated to assess its effect through controlled experiments in the laboratory. Therefore, the effects of mulch application rates and lengths on the variability of the soil loss and runoff volume can be directly evaluated at the plot scale.

The presence of straw mulch reduced by 8% (plots AR1-L10) to 42% (plots AR3-L200) the runoff volume and by 25% (plots AR1-L200) to 86% (plots AR3-L10) the soil erosion rate. The lower runoff volumes in the straw-mulched experiments compared to bare soil (control plots) are consistent with findings of several authors (e.g., Adams, 1966; ; Gholami et al., 2013; Liu et al., 2012). In every case, mulching soil with straw, also with low application rates and coarse sizes, is beneficial for improving the hydrological response of deforested soils, since the current study has demonstrated that runoff decreases at least by 7-10% and soil erosion by 25% or much more. These positive effects on soil hydrology support other hydrological and ecological advantages, such as the increase in water capacity retention and infiltrability as well as the improvement of some important physico-chemical properties (Prosdocimi et al., 2016b), which, however, go beyond the specific aims of the current paper. The current study confirms the immediate impact of straw mulch to reduce the runoff generation capacity and erosion of soils, such as Prosdocimi et al. (2016a) found in field experiments in eastern Spain under vineyard cultivation. Surface runoff and soil loss decrease in mulched soils due to three main factors. First, straw mulch has a capacity to absorb water (from 30 to 82% of the precipitation, depending on the mulch length). This water volume is retained by the straw, reducing the runoff volume. Second, the presence of straw over the soil represents an obstacle against the overland flow, which decreases the flow velocity. Third, the mulch layer protects the soil surface against raindrop impact, acting as a protection against the precipitation erosivity.

The significant capacity of straw to absorb water is beneficial, since the mulching layer decreases the share of precipitation that turns into runoff, and, therefore, the detachment capacity of the overland flow.

The decrease in the flow velocity due to the presence of straw over the soil is demonstrated by the reduction of the runoff outlet time (the lowest in the control plot and the highest in the AR3-L200 plots), which increases upon mulch length and application rate. This reduction is in accordance with findings of many authors (e.g., de Lima et al., 2019; Keesstra et al., 2019; Yanosek et al., 2006), who concluded that straw mulch is effective in delaying the runoff outlet time or runoff initiation. It is also important to noe that, when the mulch application rate and length increase, the runoff generation capacity significantly ($p < 0.05$) decreases and then the runoff outlet time is delayed. Therefore, an application rate of 3 Mg/ha with a length of 200 mm is suggested for the highest runoff reduction. These results are consistent with those of de Lima et al. (2019), who found that 10-mm mulch yielded the highest runoff.

The protection effect of straw against the precipitation erosivity helps to reduce the hydrological response of mulched soil, reducing erosion. The mulch layer protects the soil surface against raindrop impact, which is one of processes determining erosion, in addition to the transport capacity of runoff. In the current study, the lowest erosion was detected for the AR3-L10 plots, that is, in the plots with the highest mulch application rate (as for surface runoff), but the lower length. This lowest soil loss may be due to the fact that these mulch conditions lead to the highest surface cover, and, thus, the maximum soil protection. The reduced erosion with the lower surface runoff and the higher soil protection due to mulch characteristics are also confirmed by the positive correlations between total runoff, soil loss, and mulch application rate and the negative relations with surface cover as well as straw length. In other words, runoff and soil loss are associated with low values of the mulch application rate and surface cover.

The two smaller lengths of rice straw mulch (10 and 30 mm) present much more complex pathways for runoff. These pathways should enhance deposition of suspended sediments to be deposited when the flow rates decrease, while the overland flow was not influenced. In the case of the 200-mm straw, the mulch seems to increase soil erosion due to the straighter pathways. This is consistent with Rahma et al. (2017), who reported that straw mulch can induce greater soil losses compared to non-mulched soils under extreme rainfall conditions, such as those of the current study. As a matter of fact, the longer straw length resulted in greater soil losses, because the straw layer provides straighter pathways that can accelerate flow velocity and concentrate surface flow. This effect should be considered with caution when the straw length must be identified for mulching, and crushing the straw as fine as possible before land spreading for soil protection should be done.

It is interesting to note that soil erosion is not directly dependent on mulch length (that is, there is not a clear trend in soil loss reduction with straw size), but only to mulch application rate, which influences surface cover. This is confirmed by PCA, which shows direct associations among four of the five variables analyzed (runoff, soil loss, surface cover, and mulch application rate) and the first PC (which can be considered a synthetic measure of the soil hydrological response). The latter, in turn, is weakly associated with straw length. Moreover, the evident clustering of experiments provided by PCA clearly associate causes (length and application rate of straw mulch, and surface cover) and effects (runoff and soil loss). The very high correlations between the hydrological variables measured in the current study and the mulch application rate indicate that the latter is the factor with the greatest influence on the hydrological response of a deforested soil, while mulch length is more important for runoff reduction than for erosion control. For this purpose, rice straw application is beneficial to increase the surface cover, which is very effective to reduce soil loss, as shown by the high correlation between these two variables. As regards in particular the experiments done using rice straw as mulching material, de Lima et al. (2019) found in a sandy loam soil that an increase in mulch length leads to a decrease in surface cover and then in soil erosion rates.

The direct associations among the hydrological variables (runoff and soil loss), mulch parameters and soil cover found in the current study are consistent with numerous results (e.g., Donjadee & Tingsanchali, 2016; Won et al., 2012; Yanosek et al., 2006), which showed that, in soils with lower surface cover (generally with increasing mulch length), erosion expectedly increases.

4.2. Modeling runoff volume and soil loss using mulch parameters

The current study went further in the evaluation of runoff and soil loss after rainfall simulation under different mulch conditions, proposing prediction models of these hydrological variables. The multiple-regression analysis has indicated that surface runoff and soil loss can be estimated from the mulch parameters using simple but powerful equations with a linear mathematical form. The input data of these models are simply the mulch application rates and lengths. Therefore, for a given precipitation depth and intensity (as that used for these experiments), the models predict both the runoff volume and soil loss. The values of the regression coefficients of the developed equations show that the mulch application rate has much more influence than straw length (the ratio between these parameters is equal to about 200 for runoff and 400 for soil loss) and the interaction factor (that is, the product of mulch application rate by length) has a very low influence on the predicted variables. This result is consistent with the findings of Lal (1976), who demonstrated that the mulch application rate can be assumed as predictor of surface runoff and soil loss, both being significantly ($p < 0.05$) influenced by the mulch parameters. Clearly, the intercepts of the two equations are the runoff and soil loss expected under bare soil conditions. The model coefficients of ML and MAR are negative for runoff, since the latter decreases when the mulch application rate increases. Instead, these coefficients are discordant (negative for MAR and positive for ML) for soil loss, as erosion increases with coarser particles of straw and decreases for higher doses of mulch.

The developed equations are related to the precipitation variables (rainfall depth and intensity) that have been used under the simulated rainfall experiments. Therefore, for broader applications of these prediction models, a set of equations must be developed for different precipitation characteristics. For instance, having an intensity-duration-frequency curve, which gives the rainfall depth and intensity with a given return interval (that is, with a desired probability), the values of the regression coefficients can be calibrated. This helps land managers in soil conservation issues, which are pressing particularly in deforested areas, as those of the current study.

The developed models could be applied by two approaches. First, the most suitable application rate and length of mulch needed to keep the modeled hydrological variables under a tolerance limit, which, for soil loss, is in the range 3 - 11.2 Mg/ha · yr (Bazzoffi, 2009; Wischmeier & Smith, 1978). Setting up, for instance, this tolerance limit, the prediction model gives the application rate and length of rice straw mulch, which have to be applied to the soil. Second, these models can be used in combination with other erosion prediction tools, such as the well-known Universal Soil Loss Equation (USLE, Wischmeier, 1973). For instance, Eq. 3 can be used to evaluate the effect of the soil management (mathematically modeled by the USLE C-factor) on the annual soil loss, using experimental plots with the same geomorphological and climatic characteristics, but different application rates and length of rice straw mulch. The current modeling approach should go further with comparison of different straws (such as oat, barley, wheat) and under different slope and soil conditions.

In view of transferring the results of the current study to common soil conservation practice, some issues should be taken into account, such as the upscaling effects of the mulch efficacy when increasing the plot length to the hillslope scale. For instance, higher erosion rates can be observed on longer slopes, due to concentration of overland flow with increased sediment transport capacity (Rahma et al., 2017), while Prats et al. (2016), although working on soils deforested by fire, showed that smaller plots can overestimate runoff and erosion when compared to a hillslope scale. Another important issue that is likely to affect land management using straw mulch may be the risk of mulch failure over long hillslopes due to the removal effect of runoff. This risk could be evaluated by applying a modeling approach helping to identify the maximum length of slope that can be effectively protected by mulch without increased runoff and erosion rates.

5. Conclusions

Under simulated rainfall on a deforested soil treated with rice straw mulch with different application rates and lengths, runoff and soil loss in mulched soils were significantly ($p < 0.05$) lower than the corresponding variables observed for bare soil. The lowest runoff was observed for a mulch layer of 3 Mg/ha of straw with length of 200 mm. The lowest soil loss was found with the same application rates but with 10 mm length. These outcomes confirm one of the working hypotheses that higher application rates of rice straw generate less runoff and soil erosion, but reject, at least for the soil loss, the other hypothesis that to reduce the soil loss the length of rice straw must be long. The multiple-regression equations, developed to predict runoff and erosion as a function of mulch application rate and length, show very good accuracy and can be used as prediction models for identifying the most suitable mulch parameters for effective soil protection.

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