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Effects of rice straw mats on runoff and sediment discharge in a laboratory rainfall simulation

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ABSTRACT

The effects of loosely woven rice straw mats on runoff, sediment discharge, and suspended solids (SS) were investigated in laboratory rainfall simulations in an effort to identify conditions that could reduce erosion and improve water quality in farming districts. Small runoff plots of $1 \times 1 \times 0.5$ m in size were filled with loamy sand. Experimental treatments were rice straw mat cover of 0 (control), 300, 600, and 900 g m^{-2}; slopes of 10% and 20%; and rainfall intensities of 30 and 60 mm/h. Runoff volume from covered plots was significantly smaller than that from control plots at $\alpha = 0.05$. Runoff reduction by mat treatment varied between 22.1% and 100% of control values. The runoff coefficient varied with runoff volume. Sediment was dramatically reduced by rice straw mat cover. In a 30 mm/h rainfall simulation, very little sediment discharge occurred for 10% and 20% slopes. In a simulation of more severe conditions, 60 mm/h rainfall and 20% slope, no sediment was yielded if mat cover was 900 g m^{-2}. SS concentration from covered plots was significantly lower than that from controls. It was observed that once runoff occurred, even with good mulching, a certain degree of SS was likely to remain because small particulates in suspension were neither filtered nor deposited easily. Rice straw mats were proven to ameliorate runoff, sediment discharge, and SS concentration in laboratory simulations, necessitating their application in the field to validate these results.

1. Introduction

Soil erosion integrates processes that regulate rainfall infiltration and resistance of soil to particle detachment and subsequent transport. Its processes are influenced by soil properties (ex. particle size, structural stability, organic matter and the nature of clay minerals) and season (Cerdà, 1998a). Also, soil erosion is influenced by soil type and the size of the soil particle (Defersha and Melesse, 2012).

It has been known that soil erosion potential at agricultural fields is greater than that on grasslands and forest areas (Boardman et al., 1990). Intensive agricultural managements and lack of site-specific best management practices could explain accelerated soil erosion and other soil degradation processes at the rural areas (Cerdà, 2007). Generally, soil erosion potential is greater at less-vegetated areas (García-Orenes et al., 2009). Especially, intensity tillage practice and herbicide uses at the Mediterranean basin together with greater rainfall intensity (Cerdà, 1998b; Lal, 1999; Nicolau, 1996) are contributing to the removal of crop/vegetations at the surface, resulting in increased bare areas and thus, soil losses (Cerdà et al., 2009). This is why soil erosion rate is greater in agricultural fields than other land uses. To reduce runoff rate and soil losses at the agricultural fields, various studies have been attempted worldwide (Basic et al., 2001; Benik et al., 2003; Faucette et al., 2004; Locke et al., 2008; Pote et al., 2004; Tiscareno-Lopez et al., 2004). According to these studies, sediment discharge from the fields varied widely depending on surface cover and tillage implemented. Casermeiro et al. (2003) stated that runoff and soil loss are directly dependent on vegetation, but found that different plants modulate these processes differently.

Soil surface protection by crop residue cover has proven to be one of the best management practices (BMPs) for maintenance of soil health according to studies and practical applications (Pollock and Reeder, 2010). This is because pores in the soil surface are protected from clogging by small clumps of soil and organic particles detached from the soil matrix by raindrop impact. Infiltration, therefore, is not seriously reduced, and indeed can often increase with surface cover. Raindrop impact on bare and disturbed soil areas can produce soil erosion up to 225 t ha^{-1} (US DOT, 1995) and the eroded particles are the main source of this clogging (McCauley, 2005).

However, extensive quantification of soil erosion reduction of surface cover has not been implemented under natural conditions.

Thus, rainfall simulations are largely recommended for these ends (Meyer, 1994). Seeger (2007) stated that rainfall simulations are widely used for the quantification of runoff and erosion processes for different plots. Since runoff and concomitant soil erosion in agricultural fields is site-specific, their alteration by surface cover can be effectively measured through rainfall simulations (Gómez and Nearing, 2005; Meyer, 1994). Besides, many studies have been conducted to elucidate the relationships between soil surface management and runoff, sediment, and non-point source (NPS) pollution discharge. Grace et al. (1998)

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and Wilson et al. (2004) detail associations between rainfall, infiltration, and runoff through rainfall simulation studies in their respective laboratories.

The water quality of the Han River in Korea is relatively pure compared to that of other major rivers. However, the river suffers from turbidity, or elevated concentration of suspended solids (SS), largely caused by muddy runoff from alpine agricultural regions near the headwaters. The soil texture of these alpine areas, where intensive cultivation of vegetation is practiced, is mostly sand or sandy loam vulnerable to water erosion, resulting in thick muddy runoff after heavy rainfall. With the beginning of farming activities in the spring, the soil surface is completely disturbed by conventional tillage and is exposed to rainfall before the crop canopy fully develops. Serious soil erosion and sediment discharge additionally occur during the monsoon season. It is crucial to protect the soil surface from raindrop impact and maintain soil infiltration at high levels by covering the surface with protective materials such as crop residue. Because vegetable crops do not leave stable residue, the soil surface must be covered with material imported from other agricultural areas, such as rice straw. Transport, handling, and spreading of the straw over large fields are very difficult if it is not woven and compacted. Woven straw mats might effectively protect the soil surface and maintain infiltration if they covered the soil surface when necessary and were properly managed. However, the effect of rice straw mat cover on runoff and sediment discharge has not yet been addressed, which will be necessary to effectively apply straw matting to sloping alpine agricultural fields for the reduction of soil erosion and muddy runoff.

Therefore, the objective of this study was to investigate the effect of rice straw mat cover on reduction of runoff and sediment discharge through rainfall simulations under various rainfall intensities and slope conditions.

2. Materials and methods

2.1. Experimental apparatus

The main experimental apparatus consisted of three components: runoff plot, rainfall simulator, and water supply and control system (Fig. 1). A runoff plot was a soil box of 1 × 1 × 0.5 m in size. Sixteen soil boxes were made of galvanized metal sheeting. Each box was equipped with two gutters, at the top and bottom, to collect surface and subsurface runoff, respectively. The boxes were filled with soil approximating the texture in alpine agricultural areas, and saturated with water for more than two months for natural compaction and to restore soil properties. The boxes were placed on 10% or 20% steel-framed bases before rainfall simulation tests. Ladder-type rainfall simulators developed by the United States Department of Agriculture (USDA) Soil Erosion Laboratory at Purdue University, Indiana (U.S.A.) were used. Plastic water storage tanks, rainfall intensity controllers, water pumps, water supply and drainage hoses, valves, and gauges formed the control system. The simulator could simulate rainfall intensity from 20 to 100 mm/h.

Fig. 1. Rainfall simulator and soil-box (runoff plot) placement.

2.2. Experimental treatments and rainfall simulation

Experimental treatments were rice straw mat cover, slope, and rainfall intensity. Woven rice straw matting was purchased in a local market and its air-dried weight was measured. Straw mat cover treatments were 0 (control), 300 (1 layer), 600 (2 layers) and 900 (3 layers) g m^{-2}. Slope and rainfall intensity treatments were 10% and 20%, and 30 and 60 mm/h, respectively. Two sets of rainfall simulators were used after calibration with respect to different operating water pressure. Groundwater was pumped and used in simulations. A rainfall simulation experiment lasted for 60 min at both 30 and 60 mm/h intensities. Each treatment was replicated 3 to 4 times.

2.3. Measurement and analysis

Both surface and subsurface runoff volumes were collected through their respective gutters and stored independently. After measurement of runoff volume, collected runoff was sieved with a #200 mesh (0.074 mm) to separate sediment from water. The sieved sediment was air-dried and measured for sediment discharge. The rest of the water was used to measure suspended solids (SS) concentration according to standard methods for the examination of water and wastewater (APHA, AWWA, WEF, 1995). After completion of the experiment, soil samples were taken from the soil boxes and analyzed with respect to particle size distribution according to KS F 2302 (KATS, 2002) and KS F 2308 (KATS, 2006). Duncan's range test ($\alpha = 0.05$) was performed for comparisons of collected runoff and water quality data with respect to experimental treatments.

3. Results and discussion

3.1. Soil characteristics

The soil used in this study was a type of decomposed granite soil with its origin in the alpine agricultural area modeled. Particle size analysis showed that soil texture was sandy loam and coefficients of uniformity (Cu) and gradation (Cg) were 75 and 2.8, respectively. Table 1 shows the results of particle size analysis of the soil.

3.2. Surface runoff

Table 2 compares time of initial runoff, runoff volume, and runoff coefficient with respect to rainfall intensity, slope, and surface cover, establishing that the time of initial runoff was retarded with increasing weight of rice straw matting for all treatments. Runoff volume was significantly different between control and covered plots, at $\alpha = 0.05$. Runoff reduction by mat treatments ranged between 22.1% and 100%. Under 30 mm/h rainfall simulation, runoff from covered plots was negligible or nonexistent for both 10% and 20% slopes. Under 60 mm/h rainfall, which simulated high intensity precipitation, runoff from covered plots was significantly reduced relative to that from control plots. The runoff coefficient varied similarly to the runoff volume. In a 60 mm/h simulation,

Table 1
Particle size analysis of soil used in the study.

Item	Sand (%)	Silt (%)	Clay (%)	Specific gravity (Mg/m^3)
Mean	85.86	12.56	1.58	2.65
Standard deviation	1.40	1.26	0.34	0.10

Table 2
Mean comparison of initial runoff time, runoff volume, and runoff coefficient with respect to rainfall intensity (RI), slope, and weight of rice straw mat.

Runoff plot	RI (mm/h)	Slope (%)	Weight of straw cover (g m^{-2})	Initial runoff (min)	Runoff (l)	Runoff coefficient (%)
I	30	10	0	7.52	17.3^a	55.0
II	30	10	300	55.40	0.2^b	0.8
III	30	10	600	–	0^b	0
IV	30	10	900	–	0^b	0
V	30	20	0	6.13	20.6^a	70.4
VI	30	20	300	42.63	5.1^b	12.5
VII	30	20	600	–	0^c	0
VIII	30	20	900	–	0^c	0
IX	60	10	0	3.49	38.6^a	66.1
X	60	10	300	21.08	29.0^b	41.7
XI	60	10	600	40.01	2.0^c	5.9
XII	60	10	900	50.32	0.8^c	1.3
XIII	60	20	0	2.58	48.8^a	85.3
XIV	60	20	300	12.59	38.0^b	63.3
XV	60	20	600	24.58	31.4^c	34.0
XVI	60	20	900	35.23	10.0^d	16.6

Note. a, b, c, d: Mean comparison by Duncan's range test at $\alpha = 0.05$.

the runoff coefficient of 85.3% on a 20% slope was reduced to 16.6% as mat cover increased to 900 g m^{-2} (equivalent to 3 layers of matting). This meant that 83.4% of rainfall either infiltrated the soil or was absorbed by the covering material. In 30 mm/h simulations, runoff coefficients on 10% and 20% slopes were 55.0% and 70.4%, respectively. These coefficients decreased to 0.8% and 12.5% if the soil was covered with 300 g m^{-2} matting. The large reduction of runoff and flow velocity demonstrated by the low runoff coefficients could play a key role in the reduction of soil erosion and other agricultural NPS pollution discharge because tractive force and transport capacity are proportional to the power of 2 to 6× the flow volume or velocity (Choi, 1992; Woolhiser et al., 1990). Rice straw mat cover proved to be very effective in the reduction of runoff from experimental plots. Runoff decreased significantly with increasing amounts of covering material (300 g m^{-2} to 900 g m^{-2}). The greater is the quantity of covering materials, the greater is the runoff reduction observed (Fig. 2), due to complete and thick coverage of the soil surface. However, we consider that application of straw matting at 900 g m^{-2} might be impracticable in the field. Therefore, we suggest that a single layer of straw matting (300 g m^{-2}) could be more easily applied in the field for runoff reduction if the mats were spread densely and carefully to minimize bare soil surface.

The runoff reduction rates of cover material plots, compared to the control plot, were greater by 80% under rainfall intensity of 30 mm/h simulation (slopes of 10% and 20%) (Fig. 2). However, no significant difference in runoff reduction was found among surface cover materials at the 10% slope. In contrast, runoff reduction rates were significantly different under rainfall intensity of 60 mm/h simulation. According to this study, slope is an important factor impacting runoff reduction rate (Fig. 2c, d).

The results here were similar to findings reported by other authors. Jordán et al. (2010) determined that mulching with vegetation residue contributes to decrease of runoff and soil loss through an increase in infiltration, surface roughness, and interception. Puustinen et al. (2005) reported that mulching enhances infiltration and decreases runoff. García-Orenes et al. (2009) and Jordán et al. (2010) reported that soil surface was ponded if it was mulched, resulting in increasing infiltration and delaying runoff. Jordán et al. (2010) reported that soil surface mulching with residue of 5 or 10–15 Mg ha^{-1} improved rainfall infiltration to more than 90% or almost 100%, respectively, resulting in minimal or no runoff. García-Orenes et al. (2009) also reported that no runoff occurred under a 55 mm/h rainfall simulation on a 5% slope when soil was covered with residue of 2.5 Mg ha^{-1}. In this study, surface cover of 600 g m^{-2} (6 Mg ha^{-1}) evoked no runoff in rainfall simulations of 30 mm/h on both 10% and 20% slopes and very small runoff in a simulation of 60 mm/h on the 10% slope. These results demonstrated the effectiveness of surface cover on runoff reduction.

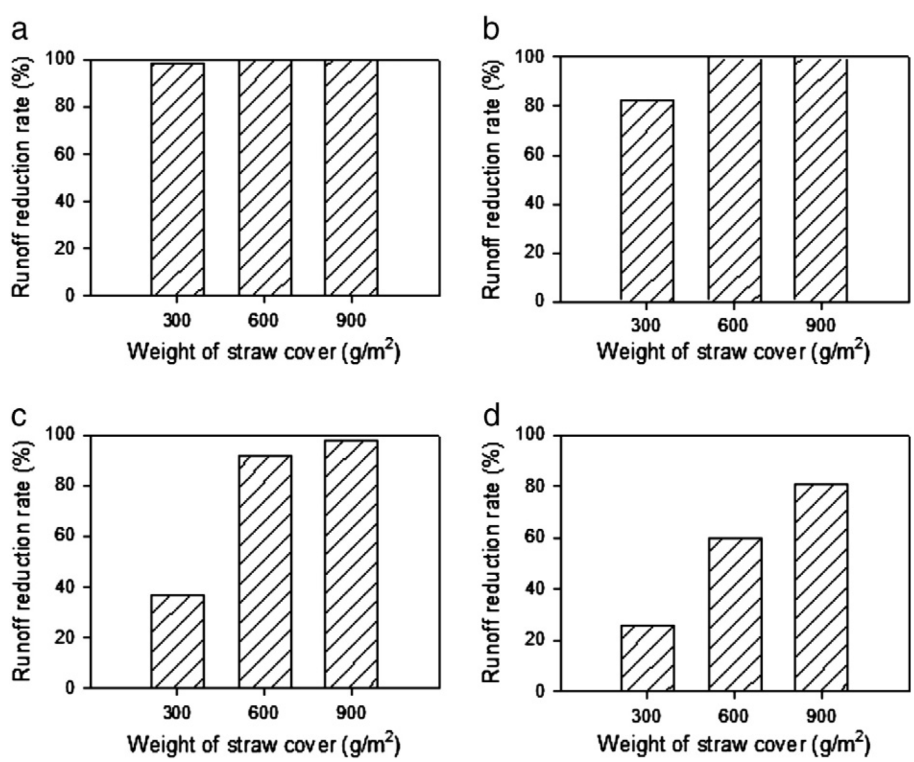

Fig. 2. Average runoff reduction rate under various rainfall intensities (RI) and slope conditions. (a) RI of 30 mm/h and 10% slope, (b) RI of 30 mm/h and 20% slope, (c) RI of 60 mm/h and 10% slope, (d) RI of 60 mm/h and 20% slope.

Table 3
Mean comparison of sediment yield and SS concentration with respect to rainfall intensity (RI), slope, and weight of rice straw matting.

Runoff plot	RI (mm/h)	Slope (%)	Weight of straw cover ($g\ m^{-2}$)	Sediment yield ($g\ m^{-2}$)	SS ($mg\ l^{-1}$)
I	30	10	0	10.3[a]	1450.0[a]
II	30	10	300	0.0[b]	155.0[b]
III	30	10	600	0.0[b]	0.0[b]
IV	30	10	900	0.0[b]	0.0[b]
V	30	20	0	53.2[a]	2855.0[a]
VI	30	20	300	2.3[b]	996.0[b]
VII	30	20	600	0.0[b]	0.0[c]
VIII	30	20	900	0.0[b]	0.0[c]
IX	60	10	0	32.6[a]	2050.0[a]
X	60	10	300	16.8[b]	708.0[b]
XI	60	10	600	2.9[bc]	698.0[b]
XII	60	10	900	0.0[c]	495.0[b]
XIII	60	20	0	261.1[a]	2930.0[a]
XIV	60	20	300	89.5[b]	1473.0[b]
XV	60	20	600	14.8[c]	605.0[b]
XVI	60	20	900	0.0[c]	568.0[b]

Note. a, b, c: Mean comparison by Duncan's range test at $\alpha = 0.05$.

3.3. Sediment discharge and SS concentration

Table 3 shows the results of mean comparison of sediment yield and SS concentration with respect to rainfall intensity (RI), slope, and weight of rice straw mat cover. Sediment was dramatically reduced with the application of rice straw mat cover. Good protective cover of the soil surface can reduce the amount of soil erosion from disturbed land surfaces occurring from raindrop impact as much as 225 $t\,ha^{-1}$ (US DOT, 1995). We conjectured that rice straw matting would be a useful covering material and protect the soil surface capably to minimize soil erosion from raindrop impact. Tractive force and transport capacity in covered plots were also minimized by runoff reduction, leading to a substantial decrease in sediment discharge. In a 30 mm/h rainfall simulation, almost no sediment discharge occurred for both 10% and 20% slopes. As the weight of covering material increased, sediment discharge declined nearly to zero even under the worst simulation, of 60 mm/h rainfall and 20% slope. Differences in sediment discharge between 600 and 900 $g\ m^{-2}$ cover plots were not significant, suggesting that the straw mat cover of 600 $g\ m^{-2}$ might minimize sediment discharge. It appeared that the impact of slope on discharge was greater than that of rainfall intensity but this could not be validated statistically.

Sediment discharge increased with increasing slope and rainfall intensity consistent with the results of Gómez and Nearing (2005). In short of the results, sediment reduction rate increased with increases in straw cover, decreases in slope and rainfall intensity (Fig. 3).

García-Orenes et al. (2009) prepared runoff plots in an orchard of 5% surface slope and effected rainfall simulations of 55 mm/h, reporting that no runoff or sediment discharge was observed from plots in which weeds naturally grew and on which 250 $g\ m^{-2}$ of oat straw were mulched during the summer dry season because, although rainfall intensity was quite high, weeds and surface mulch helped infiltrate the total simulated rainfall. Jordán et al. (2010) also reported that soil erosion was reduced if the soil surface were mulched because detachment of soil particles was reduced upon raindrop impact, infiltration increased, and runoff diminished.

We clearly demonstrate a dramatic reduction in sediment discharge as the weight of the mat applied increased; application of rice straw matting might prove a best management practice (BMP). However, small-scale experiments cannot simulate rills and gullies (Pappas et al., 2008), and practical application of rice straw matting must take this into consideration. Economical and practical applicability, soil nutrient balance (through addition of carbon-dominant materials), availability of rice straw, and other environmental factors should be carefully considered before the application of rice straw mats to sloping alpine fields.

SS concentration between control and covered plots differed significantly, as shown in Table 3. SS concentration from control plots ranged between 1450 $mg\ l^{-1}$ and 2930 $mg\ l^{-1}$. SS concentration from the mat-covered plots ranged between 495 $mg\ l^{-1}$ and 1473 $mg\ l^{-1}$, except for Plot II, where runoff was negligible. This meant that once runoff

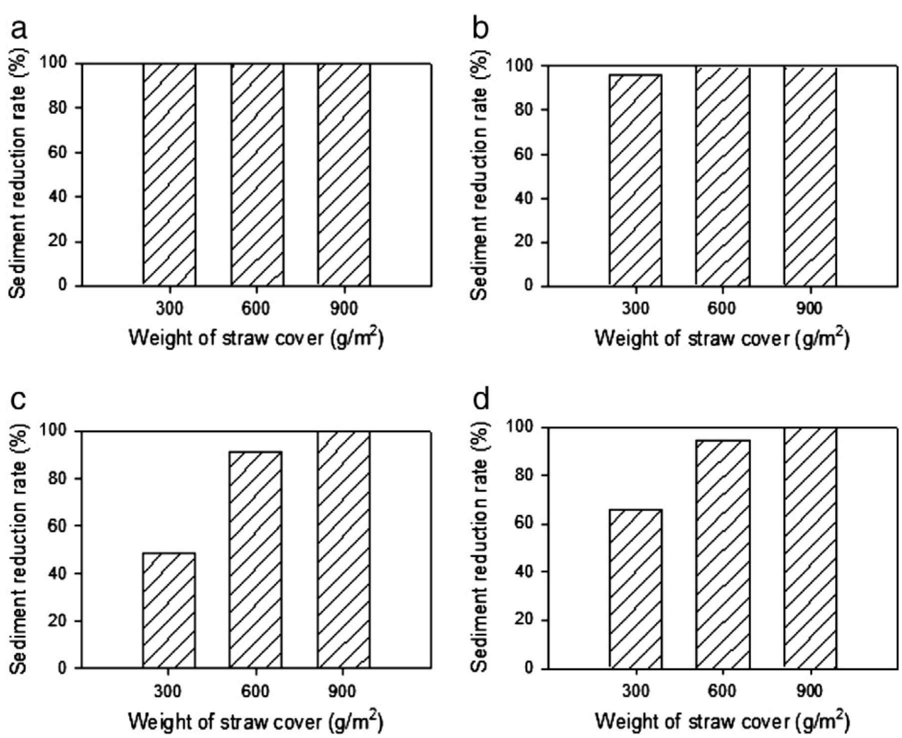

Fig. 3. Average sediment reduction rate under various rainfall intensities (RI) and slope conditions. (a) RI of 30 mm/h and 10% slope, (b) RI of 30 mm/h and 20% slope, (c) RI of 60 mm/h and 10% slope, (d) RI of 60 mm/h and 20% slope.

Table 4
Pearson correlation coefficient between measured parameters ($n=64$).

	Straw mat cover ($g\ m^{-2}$)	Initial runoff (min)	Runoff coeff. (%)	SS ($mg\ l^{-1}$)	Sediment ($g\ m^{-2}$)
Straw mat cover ($g\ m^{-2}$)	1	0.5175**	−0.7869**	−0.7374**	−0.4741**
Initial runoff (min)		1	−0.8127**	−0.5963**	−0.4730**
Runoff coeff. (%)			1	0.8653**	0.6650**
SS ($mg\ l^{-1}$)				1	0.6657**
Sediment ($g\ m^{-2}$)					1

** $p<0.01$.

occurred, SS concentration was likely to be maintained at a certain concentration due to the difficulty of filtering or depositing small particulates in suspension. As the depth of the mat applied increased, SS concentration decreased. An examination of runoff and SS concentration (Tables 2 and 3) indicated that slope was also influential for SS concentration.

SS is one of the major causes of muddy runoff in Korea. It is neither deposited well, nor removed easily, such that muddy runoff should be eliminated at the source where possible. SS is closely related to the development of rills and gullies, which in Korean alpine regions largely stems from runoff. The first requirement in runoff reduction will be to reduce runoff from sloping fields. Agricultural BMPs to meet this requirement are therefore to introduce techniques that can reduce runoff, rill and gully development, and raindrop-mediated soil erosion. Surface coverage by straw matting may prove a good alternative to current agricultural BMPs. We suggest that field application of rice straw matting will be needed to validate our laboratory results in both practical and economical aspects.

3.4. Correlation between parameters

Table 4 shows the relationships between measured parameters. Negative correlations were shown between straw mat cover and runoff coefficient, SS concentration, and sediment, while positive correlations were shown between straw mat cover and time of initial runoff ($p<0.01$). Runoff coefficient, SS concentration, and sediment were positively correlated, implying that runoff must be reduced to reduce sediment and SS concentration. A good alternative to reduce runoff from sloping alpine agricultural fields was to cover the soil surface with rice straw matting. If weaving and transportation of such mats is costly, soil could be mulched with rice straw or other vegetable residue. In this case, however, such mulching must be protected from the strong winds occurring in mountainous regions.

4. Conclusion

The effects of loosely woven rice straw mat cover on runoff, SS, and sediment discharge from small laboratory plots filled with sandy soil were investigated in rainfall simulations. Time of initial runoff was retarded as the weight of rice straw matting increased for all treatments. Runoff volume from treated plots was significantly reduced relative to that from control plots at $\alpha=0.05$. Runoff reduction by mat treatment in comparison to controls ranged between 22.1% and 100% depending on rainfall intensity and slope. Greater mat cover improved runoff reduction. Runoff coefficient varied with runoff volume. Sediment was drastically reduced by addition of rice straw matting due to the minimization of soil detachment by rainfall splashing and the reduction of runoff. In a 30 mm/h simulation, practically no sediment discharge occurred for either 10% or 20% slope. In the most extreme simulation, 60 mm/h rainfall on a 20% slope, no sediment was yielded if the mat cover was 900 $g\ m^{-2}$. However, the differences observed in sediment discharge between plots covered with 600 or 900 $g\ m^{-2}$ matting were not significant, and we would therefore recommend straw mat cover of 600 $g\ m^{-2}$ as a BMP. SS concentration from treated plots was significantly lower than that from control plots, with control SS concentrations ranging between 1450 $mg\ l^{-1}$ and 2930 $mg\ l^{-1}$, while those from treated plots were 495 $mg\ l^{-1}$ to 1473 $mg\ l^{-1}$ except for a single plot with negligible runoff. It appears that once runoff occurs, even with good mulching, a certain concentration of SS is likely to be sustained, as small particles in suspension are not easily filtered or deposited. The beneficial effects of rice straw matting on reduction of runoff, sediment discharge, and SS concentration were proven in the laboratory setting. We suggest that BMPs be adapted to reflect the necessity of reduction in sediment discharge and SS concentration for runoff reduction due to their close correlation with runoff levels.

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