Rain splash soil erosion estimation in the presence of rock fragments

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ABSTRACT

Rain splash soil erosion in the presence of rock fragments and different initial conditions was tested in laboratory flume experiments under controlled conditions. The aim of the experiments was to ascertain whether cumulative soil erosion is proportional to the area of soil exposed to raindrop detachment under the condition of constant and uniform precipitation. The surface area exposed to rain splash erosion was adjusted by placing rock fragments onto the surface of identically prepared soil in laboratory flumes. The laboratory results showed that the eroded cumulative mass depended on the cumulative runoff, and that soil erosion was proportional to the soil surface area exposed to raindrops, in situations where an initially dry, ploughed and smoothed soil surface were ensured. The results showed that this relationship was controlled to a smaller extent by the soil's initial moisture content, bulk density and soil surface characteristics. When the initial conditions were more complex, soil erosion was proportional to the area exposed only at steady state. Then, sediment concentrations during the first part of the erosion event were instead more sensitive to the initial state of the soil surface, whereas at steady state it was observed that the concentrations of eroded sediments were controlled mainly by the effective rainfall and area exposed to raindrops. Previously published field data on rain splash soil erosion were analyzed to ascertain whether the same behavior was evident under field conditions. For this case it was found that rain splash erosion is in general not proportional to the area exposed. In contrast to the controlled laboratory experiments, the field experiments were characterized by non-uniform initial surface roughness, surface soil aging and heterogeneous rock fragment size and spatial distribution. However, the presented laboratory results showed clearly that, for soils with negligible surface roughness, erosion depends on (i) the area of soil exposed to rainfall and (ii) the cumulative runoff, and that it is only slightly dependent on other soil variables.

Keywords: Soil erosion experiment, Area exposed, Flume experiment, Cumulative discharge, Cumulative eroded mass, Soil initial conditions.

1. Introduction

Over several decades, attention has been given to the effect of the soil surface characteristics (such as surface roughness, crop residues, organic mulches, vegetation cover and rock fragment coverage) on runoff generation, infiltration and soil erosion rates (Poesen and Lavee, 1991; Poesen et al., 1999; Li, 2003; Gyssels et al., 2006; Smets et al., 2008; Knapen et al., 2009; Guo et al., 2010; Zavala et al., 2010). Numerous studies have pointed out the role played by surface rock fragments on erosion as well as on the hydrological response of soils (such as infiltration rate, surface ponding, runoff generation) (Adams, 1966; Poesen et al., 1990, 1994, 1998, 1999; Abrahams and Parsons, 1991, 1994; Bunte and Poesen, 1994; Ingelmo et al., 1994; Poesen and Lavee, 1994; Torri et al., 1994; van Wesemael et al., 1995, 1996; de Figueiredo and Poesen, 1998; Abrahams et al., 2000; Li, 2003; Hung et al., 2007; Rieke-Zapp et al., 2007; Katra et al., 2008; Martinez-Zavala and Jordan, 2008; Guo et al., 2010). Most of these studies have shown that, for soils with sparse vegetation cover, such as in Mediterranean areas, rock fragments are one of the important factors controlling soil erosion yields. It has been observed that even a small amount of rock fragments incorporated in the soil matrix or placed on the soil surface can change sediment yields, steady-state infiltration, and runoff rate (Rieke-Zapp et al., 2007). Govers et al. (2006) reported that the intensity of water erosion is strongly related to the presence and density of rock fragments and vegetation (living plants and/or residues) on the soil.

The importance of rock fragments has been confirmed indirectly as well. Nyssen et al. (2001) pointed out in semiarid areas farmers are often reluctant to remove the smaller rock fragments (i.e., < 5 cm across) from their fields, since they consider that such rock fragments help soil moisture conservation and protect topsoil against soil erosion.

Poesen et al. (1994) reviewed the effect of rock fragments on soil erosion at different spatial scales and under different circumstances. They summarized the effect of the rock fragments as: (i) protecting the underlying upper soil structure against rainfall detachment, (ii) reducing the physical degradation of the eroded soil due to the dissipation of the overland flow energy, and (iii) retarding the discharge flow thus reducing entrainment and transport capacity of the overland flow. Rock fragments preserve the original soil structure (the area under the rock fragments) by intercepting and absorbing the kinetic energy of raindrops resulting in reduction of soil detachment due to raindrop splash. In addition, the presence of rock fragments on the soil surface prevents surface sealing and crusting (Poesen et al., 1999; Rieke-Zapp et al., 2007). They reduce the cross-sectional flow area and so increase the flow path, holding excess water in contact with the unsealed soil longer and allowing more infiltration into protected areas around the rock fragments (Adams, 1966; Poesen and Ingelmo-Sanchez, 1992; Abrahams and Parsons, 1994; Poesen and Lavee, 1994; Poesen et al., 1994, 1999; Li et al., 2000; Cerdà, 2001; Mandal et al., 2005; Martinez-Zavala and Jordan, 2008). However, numerous studies have pointed out that the effect of surface rock fragments and soil erosion delivery is complex and ambivalent (that is, it was observed that rock fragments might either reduce or increase erosion and runoff rates) (Poesen et al., 1990; Poesen and Ingelmo-Sanchez, 1992; Bunte and Poesen, 1994; Poesen et al., 1994, 1998; Martinez-Zavala and Jordan, 2008), depending on the features of the rock fragments (fraction of soil surface covered, rock fragment size, shape and emplacement, i.e., resting on the soil surface, partially or totally embedded in the soil).

Besides rock fragment characteristics, there are other factors that impact on the effect of rock fragment cover, including the antecedent moisture content, bulk density and initial surface roughness. Mamedov et al. (2006) emphasized that the surface conditions, in particular the antecedent moisture content and aging (i.e., wetting and keeping the soil at given moisture content), affect the soil surface structural stability as well as its resistance to seal development and soil losses. Additionally, it has been recognized that the land cover (vegetation, rock fragments) as well as seasonal wetting/drying cycles affect significantly the aggregate stability and consequently soil losses (Cerdà, 1996, 1998).

Variations in surface elevation across a field – resulting from soil erosion, wetting/drying cycles, rill formation and agricultural practices – are normally referred to as soil surface roughness (García Moreno et al., 2010). Numerous studies have investigated the effect of initial surface roughness on sediment transport predictions (Johnson et al., 1979; Cogo et al., 1983; Bertuzzi et al., 1990; van Wesemael et al., 1995; Darboux and Huang, 2005; Gómez and Nearing, 2005; Le Bissonnais et al., 2005). Poesen et al. (1994) found that the influence of surface rock fragments on interrill sediment yield depends largely on their effect on runoff generation and development of overland flow patterns. Runoff production depends on the surface hydrological connectivity (Martinez-Zavala and Jordan, 2008). For example, Jomaa et al. (2010) observed that soil surface non-uniformity leads to local barriers that form surface pools. The irregular surface affects the hydrological connectivity, and so affects the flow concentration and runoff generation and in turn soil erosion. The effect of surface roughness is more pronounced in natural environments (at the field scale) where the soil is spatially heterogeneous and the rock fragments have non-uniform size, shape and spatial distribution. As a result, in natural environments the effect of the surface rock fragments on soil erosion yields is controlled to a large extent by surface roughness (Cerdà, 2001; Mandal et al., 2005; Martinez-Zavala and Jordan, 2008). In summary, increasing surface roughness tends to increase the resistance of the original soil to raindrop detachment; it enhances the capacity of the surface to store precipitation, and it reduces the flow velocity and thus the erosive capacity of runoff (Farres, 1978; Römkens and Wang, 1987; Hairsine et al., 1992; Römkens et al., 2002).

Here, we investigate the effect of rock fragment cover on rain splash soil erosion for a soil with negligible surface roughness initially. A similar soil surface is found for example in agricultural areas after tillage, a situation that is known to enhance soil erosion (Voorhees and Lindstrom, 1984; Gómez et al., 1999). As part of the analysis, it will be feasible to answer the question: Is rain splash soil erosion proportional to the surface area exposed under the condition of negligible surface roughness? For instance, the presence of the rock fragments on the soil surface reduces the cross-sectional area available for overland flow, so for uniform rainfall the addition of rock fragments leads to an increase in overland flow depth. The latter will result in attenuation of erosion due to raindrop splash (Lavee and Poesen, 1991; Abrahams and Parsons, 1994; Abrahams et al., 2000). If this attenuation is significant then it follows that addition of rock fragments produces erosion that is not proportional to the area exposed. At the same time the increased depth of water on the surface will promote increased infiltration into the soil (e.g., Parlange et al., 1992; Barry et al., 1993, 1995), which will tend to reduce soil erosion (Sojka et al., 1993; Li et al., 2002).

2. Methods

2.1. Experimental setup

The 6-m × 2-m EPFL erosion flume was used to perform ten laboratory experiments. This rainfall simulator has been described in detail elsewhere (Tromp-van Meerveld et al., 2008; Jomaa et al., 2010). The flume is filled to a depth of 0.32 m with an agricultural loamy soil (D_{50} = 208 μm) from Sullens (Vaud, Switzerland). The grain size distribution of the original soil is shown in

Table 1. The erosion flume was divided into two identical 1-m wide flumes. Both flumes were prepared in the same manner. Before the experiment, the upper 20 cm of the original soil was plowed and gravel (> 2 cm) removed. Then, the soil surface was leveled using a mechanical system (Jomaa et al., 2010) ensuring as much as possible a smooth surface. The sampling method adopted in this study was the same described by Jomaa et al. (2010). Near-uniform precipitation (uniformity coefficient of 0.86, see van-Tromp Meerveld et al., 2008) was applied to the flumes, and samples were collected in 0.5-l bottles at the flume exit points. For each sample, the total sediment concentration was determined and the time needed to fill each bottle was recorded and used to calculate the overland flow rate as a function of time. A summary of the experimental conditions is given in Table 2.

`Table 1 near here`

`Table 2 near here`

2.2. Overview of the experiments

As mentioned, five laboratory experiments (H6, H7-E1, H7-E2, H7-E3 and H7-E4) were conducted using a pair of identical 6-m × 1-m flumes (**Error! Reference source not found.**). The experiments were carried out on a gentle slope (2.2%), but at different rainfall intensities (28 and 74 mm h^{-1}). The surface rock fragment coverage was 20 or 40%, and initial volumetric moisture content was in the range 6.52-26.36%. In each experiment, flume 1 was bare, while flume 2 was covered by rock fragments. Two experiments (H6 and H7-E1) were conducted starting from smoothed, relatively dry and disaggregated soil, whereas the other experiments were performed to ascertain the effect of different initial surface properties. To this end, the soils used in H7-E2, H7-E3 and

H7-E4 were plowed, smoothed and underwent a number of wetting/drying cycles (2-h precipitation followed by 22 h of natural air drying).

Stream power calculations were used to ascertain whether entrainment in the overland flow contributed to soil erosion (Beuselinck et al., 1999; Kinnell, 2005). According to Beuselinck et al. (2002) for loamy soils the critical stream power above which entrainment occurs is in the range 0.15-0.20 W m^{-2}. Among the experiments considered in this work, H7-E3 with bare soil had the higher runoff rate (Table 1) and therefore the largest stream power. Based on the calculations reported by Jomaa et al. (2010), the estimated stream power for H7-E3 was around 0.02 W m^{-2}, much lower than the threshold (0.15 W m^{-2}). This indicates that rain splash erosion was the dominant process in all flume experiments, and that the contributions of overland flow and rill erosion were negligible.

In the experiments, irregularly shaped natural rock fragments with diameters in the range 5-7 cm were placed on the surface (that is, they were not embedded in the soil). Rock fragments were arranged in rows transverse to the slope. The distance between the rows was 10 cm for 20% coverage and 4 cm for 40% coverage, respectively. Within each row, the distance between the rock fragments was 9 cm for 20% coverage and 3.5 cm for 40% coverage, respectively. In successive rows, the rock fragments were placed at the midpoint between the rock fragments in the preceding rows, forming a regular triangular pattern. A summary of the experiments is given in Table 2. This table reports the characteristics of each rainfall event (intensity, kinetic energy and duration), the topsoil surface properties (bulk density, initial moisture content), rock fragment characteristics (size, coverage) as well as the measured hydrological response.

`Figure 1 near here`

2.3. Overview of published experiments

The experimental data reported by Cerdà (2001), Mandal et al. (2005) and Martinez-Zavala and Jordan (2008) were used to analyze the effect of rock fragment cover on rain splash soil erosion in the field. The data were extracted from plots in these papers using the g3data software (http://www.frantz.fi/software/g3data). The particle size distributions of the soils for the three field experiments are reported in Table 1, while the rainfall simulator characteristics, the initial topsoil surface properties and rock fragment features are reported in Table 2. According to the authors, in all cases erosion was only due to rain splash, as in our laboratory flume experiments. In addition, a summary of the hydrological response observed with and without rock fragments is also listed in Table 2. Data for a bare soil condition were not available for some of the field experiments (Mandal et al., 2005; Martinez-Zavala and Jordan, 2008). These values were estimated from the measured sediment concentration with the lowest rock fragment cover assuming that erosion was proportional to the exposed area (i.e. dividing the measured sediment concentration by 1- rock fragment cover).

3. Results

3.1. Effect of surface rock fragments on hydrological response

Time-to-runoff is the period between the commencement of precipitation and the start of the first outflow at the flume exit. For experiment H6 (high rainfall and low soil rock fragment cover), the results showed that the rock fragments added to flume 2 retarded slightly the flow discharge. The time-to-runoff of flume 1 (bare soil) was 6.07 min, while that of flume 2 was 8.28 min (Table 2). In addition, the discharge from each flume differed. Using the kinematic approximation for the steady-state discharge, $q = Rl$ (l = 6 m is the length of the flume), the steady-state excess rainfall rate R of flumes 1 and 2 was 68.70 and 54.30 mm h^{-1}, respectively. The steady-state infiltration rate (I) was calculated as the difference between the rainfall intensity (P) and the steady-state excess rainfall rate (R): $I = P - R$. The infiltration rates I for flumes 1 and 2 were estimated as 5.30 and 19.70 mm h^{-1}, respectively, showing that the presence of the rock fragments increased considerably the steady-state infiltration rate as compared with the bare soil.

Experiment H7-E1 (low rainfall and high rock fragment coverage) was initially pre-wetted a few minutes before precipitation began. The effect of this change in initial moisture content was to reduce the time-to-runoff. The time-to-runoff for flume 1 was 6.07 min for H6 and 14.32 min for H7-E1, reflecting the different precipitation rates used and despite the pre-wetting used for the latter. Flume 2, which was covered by 40% rock fragments, needed 27.13 min to generate runoff. In addition, the steady-state infiltration (estimated using the runoff rate during the final 10 min of the experiment) measured in flume 2 (13.44 mm h^{-1}) was higher than that measured in flume 1 (7.54 mm h^{-1}). Thus, the results revealed that with low precipitation and with significant rock fragment coverage, the saturation of the surface soil and the attainment of steady-state flow take longer than for the case of no rock fragment coverage. The rock fragments are obstacles for the overland flow and increase the average flow path length, leading to an increase in the time-to-runoff. This in turn increases the contact time between the surface water and the soil surface, including the soil protected by the rock fragments. The protected soil (i.e., that underneath the rock fragments) is not subject to sealing and hydraulic conductivity reduction caused by raindrop impact. This mechanism has been identified as being responsible for increased infiltration in the presence of rock fragments (Poesen and Ingelmo-Sanchez, 1992; Abrahams and Parsons, 1994;

de Figueiredo and Poesen, 1998; Poesen et al., 1999; Cerdà, 2001; Mandal et al., 2005; Zavala et al., 2010).

When a different initial soil state was considered (experiments H7-E2, -E3 and -E4), the hydrological response was more rapid (Table 2). For instance, the time-to-runoff observed in experiment H7-E3 decreased to 1.23 and 2.09 min without and with rock fragments, respectively. Compared to experiment H6 (same rainfall intensity), the time-to-runoff observed in flume 1 (without rock fragments) was about five times smaller, while it was four times smaller for flume 2 (with rock fragments). The discrepancy between these two values can be attributed to the smaller rock fragment coverage and lower initial water content in H6 compared to H7-E3, which resulted in a shorter time-to-runoff. A similar conclusion can be drawn for steady-state infiltration and discharge.

3.2. Is rain splash soil erosion proportional to surface area exposed?

Results from laboratory flume experiments carried out at different rainfall intensities, rock fragment cover and initial soil properties (bulk density and initial moisture content) were analyzed to evaluate in which conditions soil erosion reduces proportionally to the exposed area. To this end, for each experiment and each flume the cumulative eroded sediment mass per unit width M [M L^{-1}] was computed using the measured sediment concentration C [M L^{-3}] and discharge rate per unit width q [L^{3} L^{-1} T^{-1}], $M = \int q(t)C(t)dt$. The mass eroded from the rock fragment-protected flume was predicted by multiplying the cumulative eroded mass on the bare soil by the fraction of exposed surface area in flume 2, and the eroded sediment concentrations were back-calculated, i.e., we approximated $C(t) = (dM/dt)q(t)^{-1}$. Cumulative erosion is, naturally, related to cumulative discharge and increases monotonically while erosion occurs.

Cumulative erosion and sediment concentrations convey slightly different information. In particular, sediment concentrations are related to the rate at which the mass of sediment increases, that is, the erosion rate. For this reason, both variables are plotted in the following against the cumulative discharge per unit width, Q [L^3 L^{-1}], $Q = \int q(t)dt$.

Fig. 2 reports the results for the experiments with initially smooth and dry surface (H6 and H7-E1). Due to the higher rainfall intensity (and longer duration of the experiment), the cumulative eroded mass collected from flume 1 (bare soil) during experiment H6 (Fig. 2, panel (a)) was considerably greater than that observed in flume 1 (bare soil) from experiment H7-E1 (Fig. 2, panel (c)). This supports well the underlying assumption of most process-based soil erosion models (e.g., Rose et al., 1983a, b; Hairsine and Rose, 1991) that erosion due to raindrop detachment is proportional to the rainfall intensity. More importantly, the agreement between the measured and estimated eroded mass for the rock fragment-protected flume was remarkably close for both experiments, despite the different precipitation rate and rock fragment cover (Fig. 2, panels (a) and (c)). This shows that, for these experiments, erosion was proportional to the exposed surface area. The corresponding sediment concentration plots (Fig. 2, panels (b) and (d)) confirm this finding, and suggest that the sediment erosion rate was proportional to exposed surface throughout the entire duration of the experiments.

`Figure 2 near here`

When the soil initial state (initial moisture content, bulk density and surface characteristics) was modified by the wetting/drying cycles (H7-E2, H7-E3 and H7-E4), the area-based predictions of cumulative mass over- (H7-E3 and E4) or under- (H7-E2) estimated the measurements (**Error! Reference source not found.**, panels (a) and (c) and Fig. 4, panel (a)). According to previous works (Farres, 1978; Le Bissonnais et al., 1995; Mamedov et al., 2006), the changes in eroded sediment mass could be attributed to the higher initial moisture content (between the two flumes and compared to the other experiments where proportionality was observed) and to compaction of the soil surface, which can be deduced from the increased bulk density (Table 2). In addition, Poesen et al. (1999) showed that rock fragments provide more protection to initially wet than to initially dry soils. One mechanism that could produce this behavior is the reduction in infiltration that accompanies the higher initial moisture content and bulk density, leading to an increased depth of surface water and, consequently, more protection from raindrop detachment (Proffitt et al., 1991; Sander et al., 1996). The sediment concentration plots for experiments H7-E2 and H7-E3 (panels (b) and (d) of Fig. 3) further complicate the picture. For these two experiments, predicted sediment concentrations are initially different from the measured values, but the steady-state values tend to fluctuate around a common value, which is suggested by the horizontal dashed line added to the plot. For H7-E2 and H7-E3 the same rainfall rate was used, and the steady-state value is in both cases achieved around Q = 50 l m^{-1}. Experiment H7-E4 (Fig 4, (a) and (b)) confirms that erosion reduces proportionally to the exposed surface area. However, due to the lower precipitation rate, the erosion yields for this experiment were small and the data relatively noisy.

`Figure 3 near here`

`Figure 4 near here`

Comparison of the soil erosion rates for these experiments suggests that sediment yields are sensitive to the initial surface condition during the initial period of an erosion event. As the soil evolves towards a new steady state, in the presence of stones the erosion rates are reduced proportionally to exposed surface area. This difference between short and long time behavior is not clearly visible from the cumulative mass plots, as the integral value accounts for the entire history of the erosion event. The effect of initial conditions was examined by comparing the cumulative mass and sediment concentrations for the bare soil flumes of the two experiments with the same precipitation rate but different initial soil surface conditions, H6 and H7-E3 (Fig. 4(c) and (d)). The results confirm that overall more sediment was discharged from the soil that was initially dry and smooth. The initial erosion rates were significantly higher in the dry and smooth soil, but the steady-state values were about the same. In addition, steady state was achieved earlier for the pre-treated soil.

Next, we investigated whether the behavior observed in our laboratory experiments was replicated in published field studies involving significantly different circumstances (initial conditions, soil properties, surface roughness, precipitation rates, slopes, rock fragment cover). Experimental data introduced in §2.3 (Cerdà, 2001; Mandal et al., 2005; Martinez-Zavala and Jordan, 2008) were again plotted as cumulative eroded mass and sediment concentrations versus cumulative discharge. Unlike the laboratory data, for these data sets soil erosion was not proportional to area exposed in the field plots. The three datasets showed consistent behavior, so only the results of Mandal et al. (2005) are discussed here, while results for the others (Cerdà, 2001; Martinez-Zavala and Jordan, 2008) are provided as supplementary material (doi:XXX). The results of Mandal et al. (2005) were selected because the experimental setup (flume dimension and raindrop kinetic energy) compares well with the above laboratory experiments. The main difference between the experiments of Mandal et al. (2005) and this study is related to the initial soil state and rock fragment pattern, that is, surface roughness, bulk density, rock fragment characteristics. The results for the experiments with a rainfall intensity of 89.2 mm h^{-1}

are reported in Fig. 5 for rock fragment cover 17.6% (panels (a) and (b)) and 41.7% (panels (c) and (d)). For the small rock fraction, the behavior is similar to that of the laboratory experiments, in that the long time erosion rates reduce proportionally to the exposed area (steady state concentration around 20 g l^{-1}), whereas predictions overestimate the initial sediment concentration. With higher surface coverage (Fig. 5, panels (c) and (d)) the proportionality was not observed. Measurements were however conducted for a relatively short period of time only, and perhaps the system did not reach steady state.

`Figure 5 near here`

4. Discussion

The aim of this study was to test in which circumstances soil erosion is proportional to the exposed surface area. The experiments analyzed above suggest that for an initially dry, disaggregated soil with negligible surface roughness, the fraction of surface area exposed to rainfall is one of the major factors controlling soil erosion yields for the entire duration of the erosion event (Fig. 2). The generality of this statement is supported to by similar findings on different soil type (e.g., Mandal et al., 2005). Instead, when the initial soil state is in a more natural condition additional factors come into play – including initial soil moisture, bulk density, rock fragment characteristics and surface roughness – and the temporal pattern of soil erosion is more complex (Fig. 3 and 4). It was observed that the predicted cumulative eroded mass – even with the same precipitation rate – in some circumstances over-estimated and in another under-estimated the measurements (experiments H7-E2 and H7-E3). The discharged sediment concentrations in the initial part of the erosion event controlled the total amount of eroded soil. In other words, when the estimated sediment concentration was higher than the measurements the predicted cumulative mass overestimated the observations (H7-E3) and vice-versa (H7-E2). The results show that initially erosion is not clearly linked solely to the exposed surface area, but that after an initial transient the erosion rates evolve towards a steady-state condition and the proportionality to exposed area appears again. This difference suggests that initially the heterogeneous conditions of the soil surface resulting from repeated wetting/drying cycles influence the short-time erosion patterns. As the rainfall event continues, the soil surface evolves again towards a steady-state condition and the erosion rates are consequently modified. Interestingly, for the laboratory flume experiments the steady-state erosion rates are independent of the initial conditions of the soil surface, but only depend on the rainfall intensity. This was suggested by the comparison of experiments H7-E2 and H7-E3, with further confirmation provided by the comparison between H6 and H7-E3 (Fig. 4d).

The lack of a proportional relationship between soil erosion and exposed surface area in the field experiments might be explained as follows. In a field soil erosion experiment, the overland flow depth is far from uniform due to the heterogonous surface roughness. Under an irregular overland flow depth the raindrop detachment would occur non-uniformly, which in turn would affect the soil erosion delivery. A rough surface affects the runoff generation due to the variable connectivity of surface flow paths. Also, in the field it has been shown that wetting and keeping the soil at given moisture content induces and increases the intra-aggregate strength between the soil particles, which decreases the soil loss (Attou et al., 1998; Mamedov et al., 2006), a process that is sometimes called aging (Attou et al., 1998). The development of a cohesive layer (or crust) on the topsoil results in surface sealing and increased roughness, which decreases the infiltration rate, again reducing soil erosion. In this context, particularly in the laboratory experiments carried out on freshly plowed soil, the presence of rock fragments protects the soil from raindrop splashes and from sealing, therefore preserving the original soil structure and infiltration rate.

The size of the rock fragments and their spatial distribution influence the soil erosion response. In natural conditions, rock fragments have heterogeneous shapes and sizes, and are randomly distributed in space. As a result, the topology of the soil surface is very irregular (high surface roughness) and the overall hydrological connectivity – at the plot level – is affected. For these reasons, both water infiltration and the soil erosion do not occur uniformly. Rather, during rainfall water accumulates in irregular local patterns leading to locally enhanced infiltration and re-deposition of suspended sediments (Heng et al., 2011). Ultimately, higher surface roughness increases the time-to-runoff, facilitates ponding, enhances infiltration and reduces soil erosion (Poesen et al., 1990; Abrahams et al., 1998; Guo et al., 2010).

5. Conclusions

The hypothesis tested in this study was that rain splash soil erosion is proportional to the area of soil exposed. The results of careful laboratory flume experiments provided clear support for this. These experiments used natural but similarly sized rock fragments, and involved different initial conditions (rainfall intensities, bulk density, rock fragment cover and initial moisture content). Two laboratory flume experiments conducted with re-plowed and smoothed soils as initial conditions showed a proportional relationship between exposed surface area and sediment delivery for the entire duration of the erosion event. Results from experiments with different and more complex initial conditions resulting from repeated wetting/drying cycles indicated that erosion rates are proportional to the exposed area only as the soil surface approaches steady state. In the initial phase of the erosion event sediment concentrations are affected by the initial conditions (such as bulk density and initial moisture content).

Published experimental data for field soils were analyzed. Here, the cumulative soil erosion was found not to be proportional to the exposed surface area alone. This difference was attributed to several additional factors such as the surface roughness, rock fragment size and spatial distribution as well as the soil surface aging. Of these factors, it is possible that, in addition to the surface area exposed, cumulative erosion is affected by surface roughness and sealing. The field data show that in all cases the measured erosion was substantially less that that estimated using only the exposed surface area. That is, in the field, it is clear that rock fragment coverage is linked to a reduction in erosion that is greater than that due to the area directly protected by the rock fragments. The proportionality between soil erosion, area exposed and effective rainfall is thus not a universal result. Indeed, in the case of our flume experiments, for soils with different initial conditions there is an initial period during which the erosion rate from the flume varies, after which a unique, area-dependent erosion rate is reached. The field results, on the other hand, show that eventually the previous history of the soil surface dominates soil erosion. We conclude that investigations into the long term surface evolution (roughness in particular and under multiple successive rainfall events) and how it controls erosion patterns would be useful to understand the transition between our laboratory results and published field experiments. Thus, further investigations are recommended to provide further insight into field behavior.

Finally, we remark in passing that the method used to analyze the data, i.e., plotting cumulative mass eroded and sediment concentration versus cumulative runoff, offers a simple means to compare experiments with, for example, different rainfall rates, soil antecedent conditions and surface roughness. In the present analysis it provides an unambiguous means by which to quantify the effect of rock fragment cover on erosion for quite different experimental circumstances.

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Table 1

Original properties of the soil used in this study and soils used in the field experiments extracted from the literature. Mandal et al. (2005) and Martinez-Zavala and Jordan (2008) performed four field experiments using slightly different soils. Here, the average of their soil grain size fractions is presented. In this study the fraction of the fine gravel (> 2 mm) was measured and differentiated from the rock fragment cover, however, in the other studies (Cerdà, 2001; Mandal et al., 2005; Martinez-Zavala and Jordan, 2008) it was considered in the rock fragment fraction.

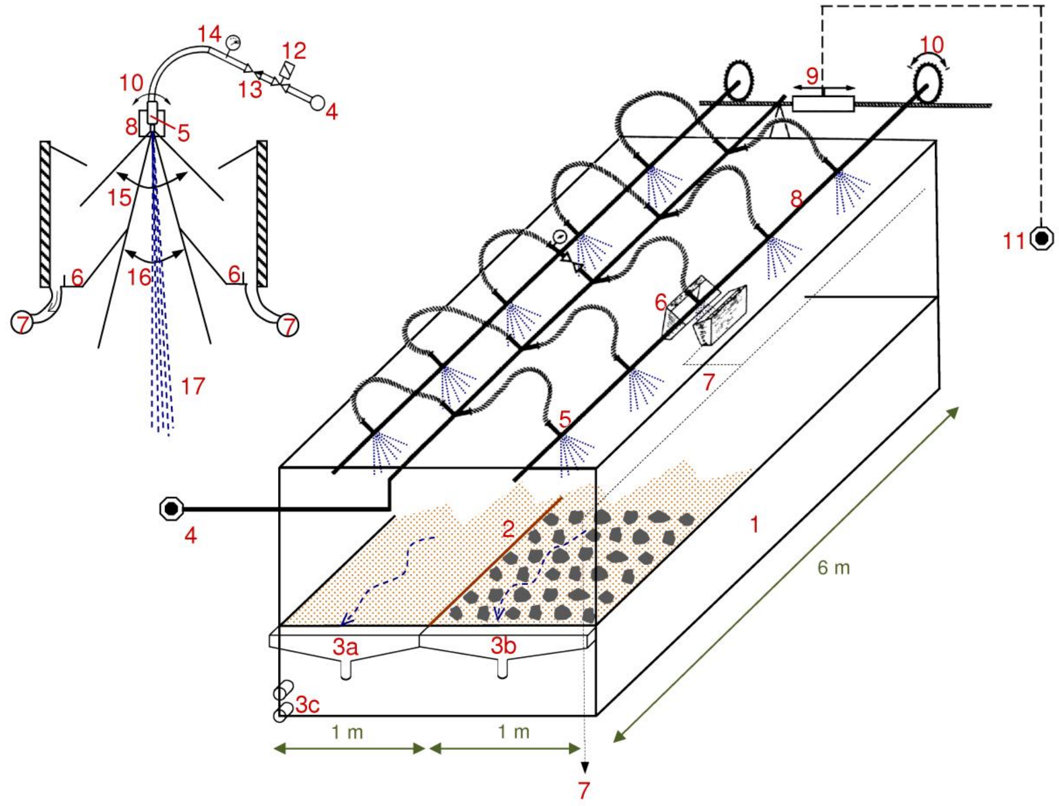
Soil properties	Clay (%)	Silt (%)	Sand (%)	Fine gravel (%)
This study	4.00	29.00	41.00	26.00
Cerdà (2001)	55.73	22.02	22.25	-
Mandal et al. (2005)	31.80	11.85	56.35	-
Martinez-Zavala and Jordan (2008)	34.46	12.42	53.12	-

Table 2. Summary of EPFL flume experiments and published data sets. The five experiments H6 and H7-E1 – H7-E4 were performed with rock fragment coverage (as listed below) and with bare soil, giving a total of 10 experiments.

Experiments	Kinetic energy (J m^{-2} mm^{-1})	Duration (min)	Rock fragment cover (%)	Precipitation (mm h^{-1})	Rock fragments size (cm)	Slope (%)	Bulk density (g cm^{-3})	Initial topsoil moisture content (%)		Time-to-runoff (min)		Steady-state discharge (mm h^{-1})		Steady-state infiltration (mm h^{-1})		Flume dimension
								With***	Without	With	Without	With	Without	With	Without	
H6	24	180	20	74	5-7	2	1.11	6.52	6.81	8.28	6.07	54.30	68.70	19.70	5.30	6 m × 1 m
H7-E1*		120	40	28			1.14	8.84	7.74	27.13	14.32	14.56	20.46	13.44	7.54	
H7-E2			40	74			1.53	24.79	19.15	2.06	1.34	63.84	71.40	10.16	2.60	
H7-E3			40	74			1.61	25.20	20.42	2.09	1.23	67.92	72.04	6.08	1.96	
H7-E4			40	28			1.64	26.36	22.14	2.46	1.58	25.80	26.76	2.20	1.24	
Cerdà (2001)**	-	60	77.43	55	> 0.2	12-17	1.15	1.14	18.36	4.61	2.13	11.17	37.06	43.83	17.94	circular (1 m^2)
Mandal et al. (2005)	27.1	50	3.5	48.5	2-8	1.2	1.56	3.1	-	7.41	-	24.87	-	23.63	-	2 m × 0.75 m
	28.8			89.2						5.23	-	61.50	-	27.70	-	
	29			136.8						2.78	-	101.20	-	35.60	-	
	27.1	50	17.6	48.5	2-8	1.7	1.59	2.6	-	7.98	-	12.84	-	35.66	-	
	28.8			89.2						6.50	-	45.80	-	43.40	-	
	29			136.8						4.81	-	83.79	-	53.01	-	
	27.1	50	41.7	48.5	2-8	1.9	1.62	1.6	-	8.90	-	2.40	-	46.10	-	
	28.8			89.2						5.73	-	16.80	-	72.40	-	
	29			136.8						5.18	-	51.97	-	84.83	-	
	27.1	50	64.7	48.5	2-8	1.6	1.62	2.0	-	9.48	-	0.58	-	47.92	-	
	28.8			89.2						8.48	-	11.80	-	77.40	-	
	29			136.8						7.5	-	59.40	-	113.57	-	
Martinez-Zavala and Jordan (2008)	4	70	3.7, 21.1, 52, 75.5	50, 100, 150	2-10	1.4-1.8	1.41-1.46	2.8-3	-	5.11-8.39	-	0.8-119.1	-	13.90-120.90	-	0.25 m × 0.25 m

[*] The topsoil surface was gently pre-wetted for a short time using a sprinkler before precipitation commenced.

[**] This experiment was characterized by three stages. First, rainfall was applied for 1 h over an area covered by rock fragments; second, the rainfall was halted for 10 min during which the rock fragments were removed; and third, the rainfall was applied again.



1. Erosion flume
2. Flume divider
3. Flow collection troughs
    a. Flume 1
    b. Flume 2
    c. Subsurface flow
4. Lake water supply
5. Water outlet tube
6. Collection troughs
7. To storm water drain
8. Rotating bar
9. Oscillator
10. Direction of oscillation
11. Compressor
12. Magnetic vane
13. Regulator
14. Manometer
15. Maximum oscillation amplitude (α = 90°)
16. Actual water outlet (β = 30°)
17. Water jet

Fig. 1. Schematic overview of the EPFL erosion flume (modified from Tromp-van Meerveld et al., 2008). Note that the drainage system (item 3) was modified for the present experiments and that the flume was divided into two sections using the flume divider (item 2). The soil surface of flume 1 remained bare, while flume 2 was covered with fluvial rock fragments, arranged in a regular triangular pattern.

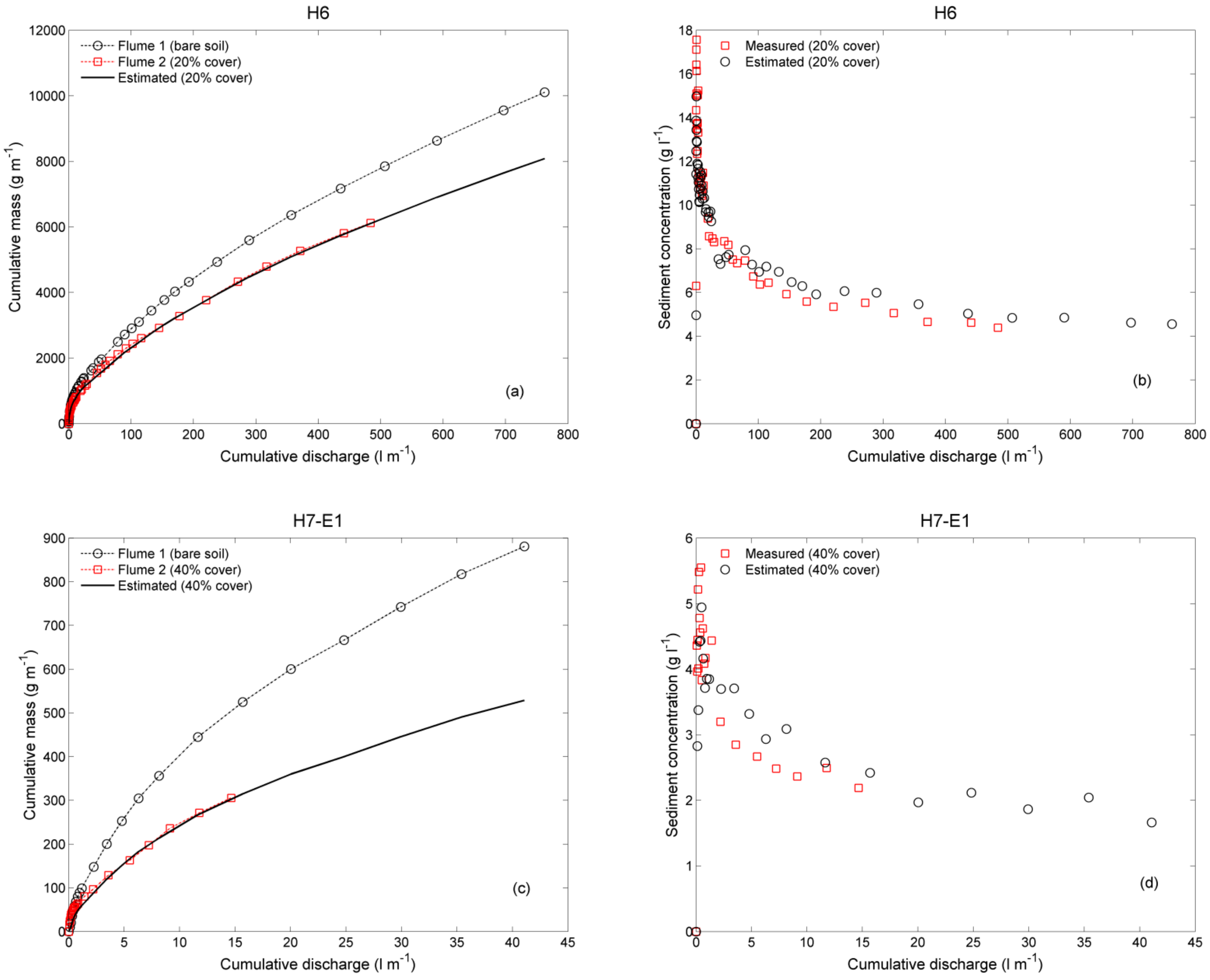


Fig. 2. Cumulative eroded mass as a function of the cumulative discharge collected from experiments H6 and H7-E1 are illustrated in panels (a) and (c), respectively. The exposed area-based estimation (solid line) reproduces satisfactorily the experimental data observed in both experiments. The corresponding measured and estimated sediment concentrations as a function of the cumulative discharge are shown in panels (b) and (d).

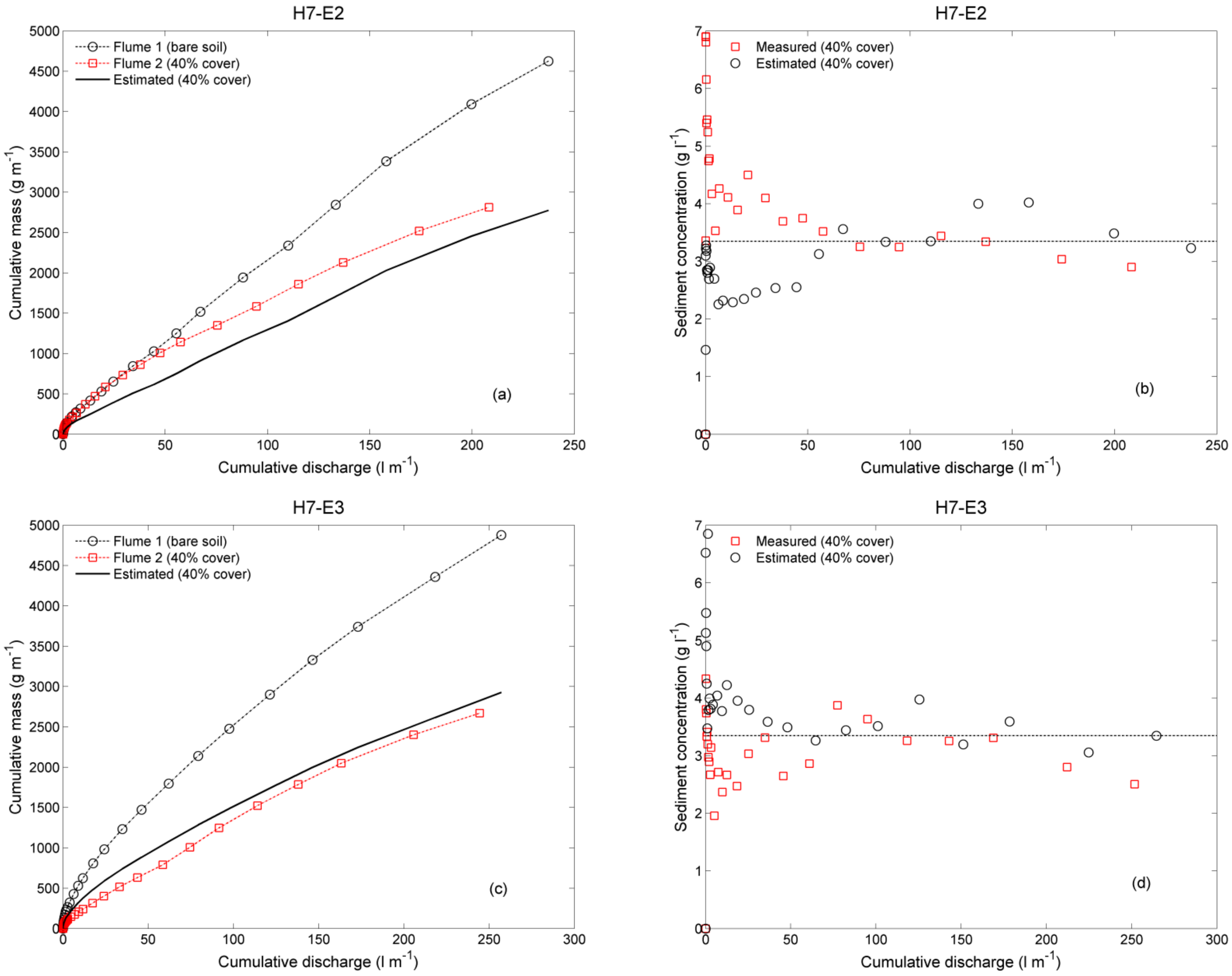


Fig. 3. Cumulative eroded mass as a function of cumulative discharge for experiments H7-E2 and H7-E3 (panels (a) and (c)). The comparison between experiments (red dashed line) and estimation (solid line) is less satisfactory than experiments H6 and H7-E1 (Fig. 1). The sediment concentration plots for the same experiments (panels (b) and (d)) indicate that the mismatch between estimates and observations occurs in the first part of the experiment. This comparison highlights that the soil erosion is proportional to area exposed to raindrop and effective rainfall at steady state but not at short times, when the different initial conditions affect the erosion from the flumes.

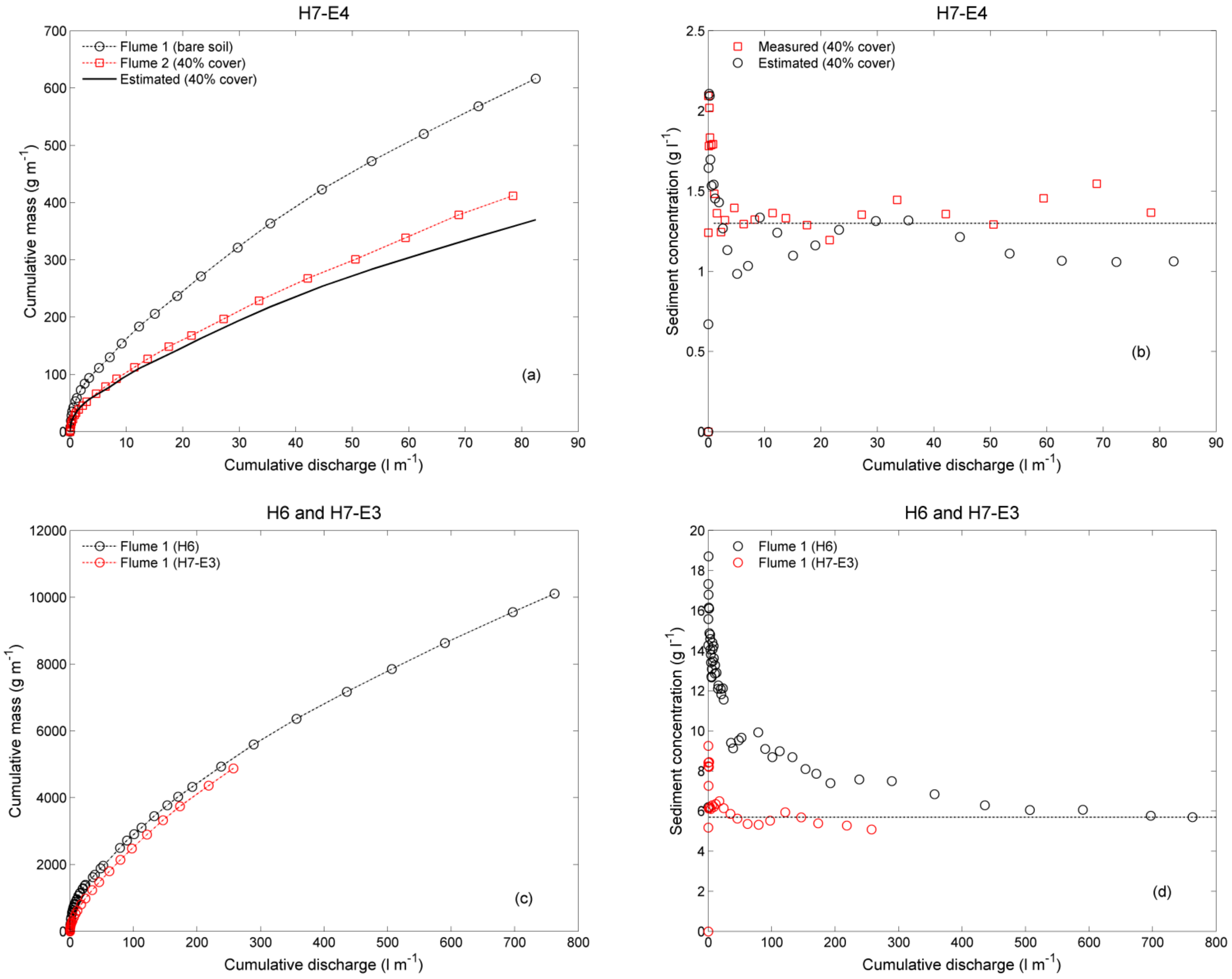


Fig. 4. Cumulative eroded mass (panel (a)) and sediment concentration (panel (b)) as a function of cumulative discharge for experiment H7-E4. The estimated eroded mass (solid line) underestimates the measurements, in particular at steady state. Note, however, that the sediment concentrations and total eroded mass are smaller than in the previous experiments. Panels (c) and (d) illustrate the results of flume 1 (bare soil) for experiments H6 and H7-E3. These experiments were performed using the same rainfall intensity, but at different bulk density and initial moisture content. The two experiments reach nearly the same steady-state concentration, although the concentrations in the initial period are markedly different. The horizontal broken lines in (b) and (d) are estimates of the steady-state sediment concentrations exiting the flume.

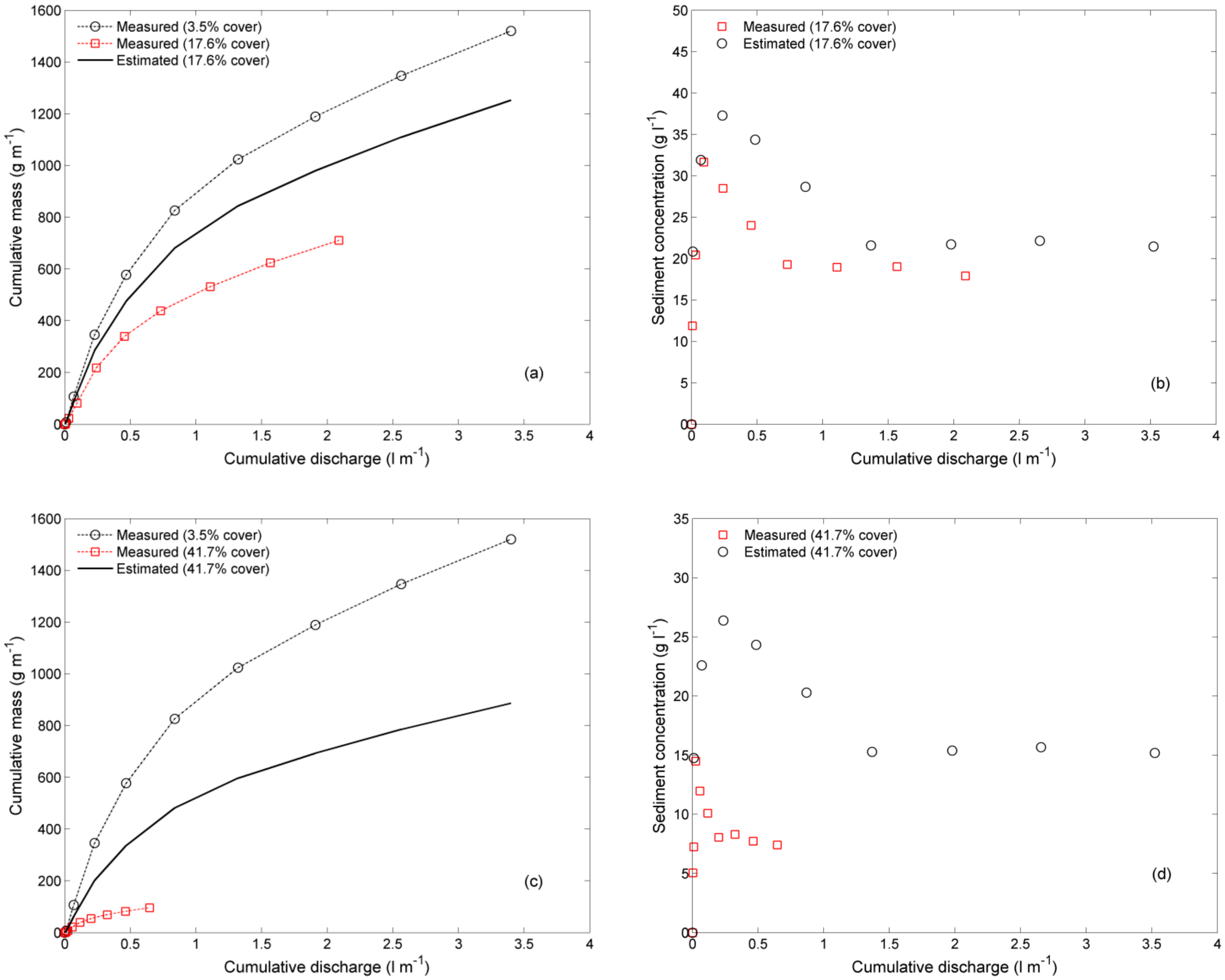


Fig. 5. Cumulative eroded mass as a function of cumulative discharge for one of the field experiments of Mandal et al. (2005) using a precipitation of 89.2 mm h^{-1}. Two rock fragment coverages are 17.6% (panels (a) and (b)) and 41.7% (panels (c) and (d)). In both cases, the estimated sediment concentration using the area-based concept overestimates the measured sediment concentrations, although the steady-state values with low rock fragment cover are comparable to the estimations. The difference compared to the laboratory experiments is attributed to the more pronounced effect of soil roughness and soil sealing in the field.