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Reduced raindrop-impact driven soil erosion by infiltration

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Deposition

Summary We used a simple laboratory experiment to investigate whether infiltration influences raindrop-impact induced soil erosion. There was substantially less erosion under infiltration conditions than with no infiltration. This was because a ''shield'' layer of deposited particles developed more rapidly under infiltration compared to ''no-infiltration'' conditions. Interestingly, the ''shield'' depth that fully protected the underlying soil from raindrop-impacts was shallower under infiltrating conditions. We found that the Rose soil erosion model captured the erosion dynamics well ($R^2 \approx 0.9$). Predicting the ''full-shield'' depth remains unresolved. These results add evidence to previous studies indicating that saturated, slowly draining areas in the landscape are particularly susceptible to soil erosion from raindrop impact.

Introduction

After more than a half-century of intense study, water-induced soil erosion mechanisms continue to stir controversy. It is widely recognized that upland erosion is largely initiated by the impact of raindrops on the soil surface (e.g., Kinnell, 1982Morgan, 1995), a process that has been recently investigated using some simple, small-scale experiments that allow researchers to isolate the role of raindrop impact from overland flow (e.g., Heilig et al., 2001; Gao et al., 2003; Gao et al., 2005). These studies have also corroborated various aspects of the Rose model, a mechanistic model of soil erosion on a hillslope (e.g., Rose and Dalal, 1988; Hairsine and Rose, 1991; Rose et al., 1994; Hairsine et al., 1999), adding to findings from other researchers that used more complicated, and realistic, experiments (e.g., Proffitt et al., 1991; Sander et al., 1996; Rose et al., 1998; Parlange et al., 1999). The objectives of this short study were to see if infiltration influences soil erosion due to raindrop-

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impact and to test the Rose model's ability to correctly capture these influences. It is traditionally recognized that reduced infiltration may lead to increased surface runoff, which can be extremely erosive (e.g., Meeuwig, 1970; Bradford et al., 1987; Shakesby et al., 2000; Nord and Esteves, 2005). Interaction between infiltration and raindrop-impact driven erosion in the absence of runoff shear forces has not been directly studied. There is good evidence that reduced infiltration will increase raindrop-impact erosion, but it is often difficult to see the effects of raindrop impact in the absence of other processes (e.g., Torri et al., 1999) or specific soil properties like hydrophobicity (e.g., Terry and Shakesby, 1993) and surface sealing (e.g., Bradford et al., 1987). Therefore, in this study we have chosen to use a simple soil structure in order to isolate the interactions between infiltration and raindrop-impact erosion.

Brief review of the Rose model (Hairsine and Rose, 1991) for raindrop-impact erosion

We characterize soil as being composed of I particle classes of equal mass and differentiated by settling velocity. The mass balance for particle class i is:

$$\frac{\partial(Dc_i)}{\partial t} + \frac{\partial(qc_i)}{\partial x} = e_i - r_i - d_i \qquad (1)$$

where D is the depth of surface flow (l), c_i is the suspended sediment concentration of class size i in the overland flow (Ml^{-3}), q is the volumetric water flux per unit width of slope ($\mathrm{l}^2\mathrm{T}^{-1}$), and e_i, r_i, and d_i are the rates of ejection of original soil, re-ejection of deposited material, and deposition, respectively.

One unique aspect of the Rose model is the development of a "shield" layer composed of deposited particles. As the shield layer develops, the underlying soil is increasingly protected from erosion by raindrops. The ejection or erosion rate, e, is therefore described as:

$$e = \frac{ap}{I}(1 - H) \qquad (2)$$

where p is the rain rate (lT^{-1}), a is the soil detachability (Ml^{-3}], and H is the shielding parameter, i.e., $H = 0$ indicates no shield formation and $H = 1$ indicates complete shielding and no additional erosion of the underlying material, and can be estimated as:

$$H = \frac{M_\mathrm{d}}{M_\mathrm{d}^*} \qquad (3)$$

where M_d is the accumulated mass of deposited material and M_d^* is the mass of material needed to completely shield the soil.

We typically assume, in the absence of infiltration, that suspended particles will settle out of the surface runoff according to Stoke's law, so that the d_i is dependent on the particle class's size and weight. In the presence of infiltration, the downward flux of the infiltrating water will also contribute to the settling rate and we assume the deposition rate of particles that would normally remain suspended will be equal to the rate of infiltrating water.

Methods

Our experimental apparatus was essentially the same as Gao et al. (2003); Gao et al. (2004); Gao et al. (2005). Briefly, pre-saturated soil was placed in a small plexiglass cylinder (diameter = 7.5 cm). Four small holes in the cylinder's walls maintained a constant ponding depth and a hole in the bottom of the cylinder allowed water to drain from the soil. To facilitate drainage, the soil rested on a porous plate (0.5 cm thick, pour sizes of 45–90 μm) below which the column was filled with glass beads (diameter of 4 mm) and a second porous plate to keep the beads from falling out of the chamber (Fig. 1); free drainage from our column was 0.0041 cm min^{-1}. The bead-layer and porous plate were saturated prior to adding the soil. The soil was a homogeneous mixture of 90% black sand (180–212 μm) and 10% white clay (hydrous Kaolin supplied by Englehard Corp., NJ), by mass (i.e., $I = 10$), pre-saturated at a ratio of 3 g soil to 1 g water. As noted earlier, this simple soil largely removes many complicating processes that would be present in a natural soil and, because the sand and clay are contrasting colors, we can easily see the "shield" layer (e.g., see photographs in Heilig et al., 2001). The soil column was placed ~3 m below a computer-controlled rain maker at the soil and water laboratory in Cornell University's Biological and Environmental Engineering Department. The rain intensity was constant for all experiments (0.115 cm min^{-1}); measured once for each experiment. An initial 0.6 cm ponding depth was attained by placing a piece of wetted filter paper directly on the soil surface while water was slowly added. The filter paper minimized disturbance to the soil surface and was carefully removed once the ponding depth was achieved. Samples of the ponded water were taken every 15 s over the first 10 min of each experiment; samples were taken using a pipette, which was inserted into one of the overflow holes and the sample size was < < 1% of the total volume of ponded water. Each experiment was videotaped and run until the ponded water became completely clear indicating complete formation of the shield. The video was used to confirm that we had steady conditions throughout each experiment, e.g., check to see if the depth of ponded water changed substantially. We ran experiments under no-infiltration and free-drainage conditions and each was duplicated. We measured clay concentrations with a spectrophotometer (wavelength = 590 nm). At the end of each experiment we carefully removed, dried, and weighed the erosion shield to measure its final mass, M_d^*. As a check, we also back-calculated M_d^* as nine times the total mass of

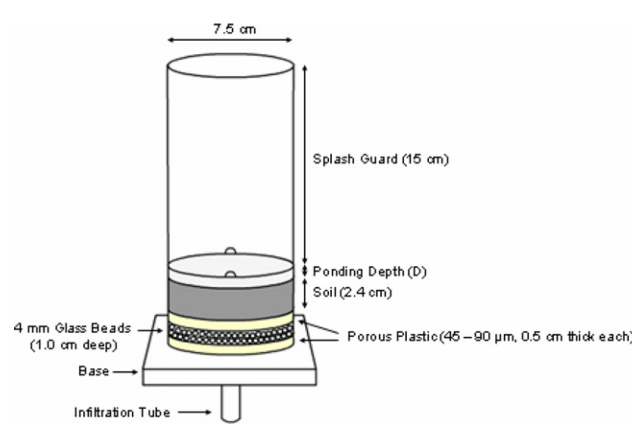

Figure 1 Schematic of the experimental soil chamber.

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clay that was eroded. We observed no sediment on the splash guard at the end of the experiments; thus, all sediment either left the chamber with the overland flow or remained in the soil column.

Following Heilig et al. (2001); Gao et al. (2003); Gao et al. (2005), we assumed that the sand particles settle instantaneously and the clay, in the absence of infiltration, has a settling velocity of zero; henceforth we are modeling for the clay unless otherwise noted. Overland flow export of clay is $q{\cdot}c$ and the overland flow, q, from the system is constant:

$$q = p - f \tag{4}$$

where f is the constant infiltration rate and p is the rain rate. The deposition rate of the clay is assumed to be proportional to the infiltration rate

$$d = f \cdot c \tag{5}$$

Knowing the sand:clay ratio in our original soil (9:1), the rate of sand accumulation in the shield can be calculated by substituting Eq. (3) into Eq. (2) and multiplying Eq. (2) by 9, i.e., $\mathrm{d}M_\mathrm{d}/\mathrm{d}t = 9e$:

$$\frac{\mathrm{d}M_d}{\mathrm{d}t} = ap\frac{9}{I}\left(1 - \frac{M_\mathrm{d}}{M_\mathrm{d}^*}\right) \tag{6}$$

Our experiment is designed to have a small infiltration rate relative to rain intensity, thus, the rate of clay deposition into the shield is negligible compared to the potential for rain to re-entrain the deposited clay. Thus, we assume that the shield is essentially completely composed of sand and can we can rewrite Eq. (3) by solving Eq. (6) for M_d:

$$H = 1 - \exp\left(-\frac{ap}{M_\mathrm{d}^*}\frac{9}{I}t\right) \tag{7}$$

Because D is constant in our experiments, Eq. (1) can be simplified by substituting Eqs. (2), (4), and (5) for e, q, and d, respectively, and Eq. (7) for H:

$$\frac{\mathrm{d}c}{\mathrm{d}t} = \frac{1}{D}\left(\frac{ap}{I}\exp\left(-\frac{ap}{I}t\right) - (q+f)c\right) \tag{8}$$

Note that ''$q + f$'' in Eq. (6) can be replaced by ''p'' (Eq. (4)), which is the same form of the model used by Heilig et al. (2001); Gao et al. (2005), who have previously shown that the solution is:

$$c(t) = \frac{a}{10 - \frac{aD}{M_\mathrm{d}^*}}\exp\left(-\frac{p}{D}t\right) \times \left[\exp\left[\left(\frac{1}{D} - \frac{a}{10M_\mathrm{d}^*}\right)pt\right] - 1\right] \tag{9}$$

Results and discussion

The general behavior of suspended clay concentrations over time are similar to previous results (Heilig et al., 2001; Gao et al., 2005), with a rapid increase in concentration which slows and then dilutes as the shield develops and clay flows from the chamber (Fig. 2). However, with infiltration, this progression is substantially faster (Fig. 2). It is remarkable how large an effect infiltration had on erosion rates given that the infiltration rate (free drainage) was so small. We ran one experiment at a ~20% higher infiltration rate (Table 1) by putting a small amount of suction on the bottom of the column with a peristaltic pump and observed an associated additional decrease in soil erosion (Fig. 2).

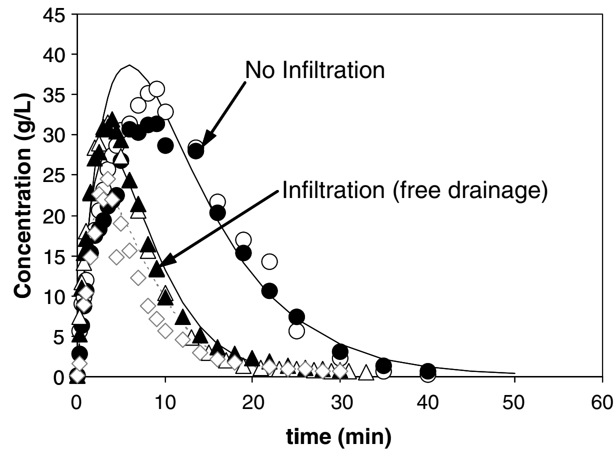

Figure 2 Experimental clay concentrations (symbols) and the associated Rose model results (lines); circles = no infiltration, triangles = infiltration with free drainage, diamonds = increased infiltration (one replicate only). The filled and open symbols are for replicate experiments.

Interestingly, and perhaps counter-intuitively, the shield depth at the end of the infiltration experiments (0.4 ± 0.1 cm) was much shallower than with no infiltration (~0.8 ± 0.1) cm) and M_d^* was considerably smaller for infiltration (Table 1). The shield was even smaller for our higher infiltration experiment, although we cannot draw any strong conclusions based on a single experimental run. One possible explanation for this is that the density of the shallow, infiltration-induced shield (i.e., M_d^*/shield depth) was ~30% higher than for the free-draining, infiltration case than in the no infiltration case and, thus, may have been more resistant to raindrop impact. Another speculative explanation might be that some drop energy was absorbed as water moved into the soil under infiltration, thus, less energy was transferred to soil ejection.

We applied the Rose model (Eq. (7)) to our experiments and were able to achieve good corroboration with our experimental data (Fig. 2; Table 1). Although we found that the best-fit soil detachability, a, varied from 1150 mg cm^{-3} with infiltration to 800 mg cm^{-3} for no infiltration, our results were not very sensitive within this range and we found that the model using a = 800 mg cm^{-3} agreed with the data nearly as well as the best-fit a values (Fig. 2 uses a = 800 mg cm^{-3} for all experiments).

Of course this simple study was designed to isolate the role of infiltration on raindrop-impact driven erosion. Natural soils contain components like organic matter, calcium carbonates, and various oxides that will undoubtedly play important and possibly complex roles in raindrop-impact erosion. However, our results suggest that inasmuch as these characteristics influence infiltration, they will play an associated role in erosion as shown here. Indeed, there are many other factors that will contribute to raindrop-impact erosion and, although many require attention (e.g., surface sealing), some have already been investigated, e.g., the effect of ponded water in absorbing raindrop-impacts (e.g., Gao et al., 2003) and how rain intensity influ-

Table 1 Parameter values and R^2 statistic for the experiments, except for the ''*Fast infiltration*'' experiment, values are averages from duplicate runs and in all cases variability was below the significant digits shown

	f (cm/min)	D (cm)	a[a] (mg/cm^3)	M_1^* (mg/cm^2)	R^2
No infiltration	0	0.6	800	101	0.91/0.99
Infiltration (free drainage)	4.1×10^{-3}	0.6	800	67	0.98/0.99
Fast infiltration[b]	4.9×10^{-3}	0.7	800	56	0.94

[a] Although we found unique best-fit a values of 800, 1150, and 1050 mg cm^{-3} for no infiltration, infiltration (free drainage), and fast infiltration, respectively, a = 800 mg cm^{-3} worked nearly as well for all experiments.
[b] Attempts to increase infiltration beyond free drainage resulted in an unstable system, note the slightly higher D, and we were only able to complete one marginally acceptable experiment.

ences raindrop-impact erosion (e.g., Heilig et al., 2001). By understanding the roles of individual processes in isolation, we can start to develop better hypotheses about how these processes may interact.

Conclusions

Using a simple soil erosion experiment, we found that infiltration profoundly reduces soil erosion from raindrop-impact. It had been widely recognized that low infiltration rates can lead to high erosion rates due to increased surface runoff, but these results indicate that soil erosion may increase even in areas where there is not substantial overland flow. The Rose model captures the behavior, although further work is needed to develop predictive models of shielding behavior. Although the simple soil composition used here helped isolate the specific role that infiltration plays, additional experimentation is needed to see how significant the role of infiltration is in the context of natural soils' more complex composition. Based on our findings, we speculate that soil (or landscape) characteristics that promote infiltration will probably reduce susceptibility to raindrop-impact erosion.

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References

Bradford, J.M., Ferris, J.E., Remley, P.A., 1987. Interrill soil-erosion processes 1. Effect of surface sealing on infiltration, runoff, and soil splash detachment. Soil Science Society of America Journal 51 (6), 1566–1571.
Gao, B., Walter, M.T., Steenhuis, T.S., Parlange, J.-Y., Nakano, K., Rose, C.W., Hogarth, W.L., 2003. Investigating ponding depth and soil detachability for a mechanistic erosion model using a simple experiment. Journal of Hydrology 277, 116–124.
Gao, B., Walter, M.T., Steenhuis, T.S., Hogarth, W.L., Parlange, J.-Y., 2004. Rainfall induced chemical transport from soil to runoff: Theory and experiments. Journal of Hydrology 295 (1-4), 291–304.
Gao, B., Walter, M.T., Steenhuis, T.S., Parlange, J.-Y., Richards, B.K., Hogarth, W.L., Rose, C.W., Sander, G., 2005. Investigating raindrop effects on the transport of sediment and non-sorbed chemicals from soil to surface runoff. Journal of Hydrology 308, 313–320.
Hairsine, P.B., Rose, C.W., 1991. Rainfall detachment and deposition: sediment transport in the absence of flow-driven processes. Soil Science Society of America Journal 55, 320–324.
Hairsine, P.B., Sander, G.C., Rose, C.W., Parlange, J.-Y., Hogarth, W.L., Lisle, I.G., Rouhipour, H., 1999. Unsteady soil erosion due to rainfall impact: A model of sediment sorting on the hillslope. Journal of Hydrology 220, 115–128.
Heilig, A., DeBruyn, D., Walter, M.T., Rose, C.W., Parlange, J.-Y., Sander, G.C., Hairsine, P.B., Hogarth, W.L., Walker, L.P., Steenhuis, T.S., 2001. Testing a mechanistic soil erosion model with a simple experiment. Journal of Hydrology 244, 9–16.
Kinnell, P.I.A., 1982. Laboratory studies on the effect of drop size on splash erosion. Journal of Agricultural Engineering Research 27, 431–439.
Meeuwig, R.O., 1970. Infiltration and soil erosion as influenced by vegetation and soil in northern Utah. Journal of Range Management 23 (3), 185–188.
Morgan, R.P.C., 1995. Soil Erosion and Conservation, second ed. Addison Wesley Longman Group Unlimited, London, UK.
Nord, G., Esteves, M., 2005. PSEM_2D: A physically based model of erosion processes at the plot scale. Water Resources Research 41 (8). Art. No. W08407.
Parlange, J.-Y., Hogarth, W.L., Rose, C.W., Sander, G.C., Hairsine, P.B., Lisle, I.G., 1999. Note on Analytical approximations for soil erosion due to rainfall impact and for sediment transport with no inflow. Journal of Hydrology 217, 149–156.
Proffitt, A.P.B., Rose, C.W., Hairsine, P.B., 1991. Rainfall detachment and deposition: Experiments with low slopes and significant water depths. Soil Science Society of America Journal 55, 325–332.
Rose, C.W., Dalal, R.C., 1988. Erosion and runoff of nitrogen. In: Wilson, J.R. (Ed.), Advances in Nitrogen Cycling in Agricultural Ecosystems. CAB International, Wallingford, England, pp. 212–235.
Rose, C.W., Hogarth, W.L., Sander, G., Lisle, I., Hairsine, P., Parlange, J.-Y., 1994. Modeling processes of soil erosion by water. Trends in Hydrology 1, 443–451.
Rose, C.W., Parlange, J.-Y., Lisle, I.G., Hogarth, W.L., Hairsine, P.B., Sander, G.C., 1998. Unsteady soil erosion due to rainfall impact and sediment transport. In: Morel-Seytoux, H. (Ed.), Hydrology Days, 18. AGU Pub, pp. 245–258.
Sander, G.C., Hairsine, P.B., Rose, C.W., Cassidy, D., Parlange, J.-Y., Hogarth, W.L., Lisle, I.G., 1996. Unsteady soil erosion

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model, analytical solutions and comparison with experimental results. Journal of Hydrology 178, 351–367.

Shakesby, R.A., Doerr, S.H., Walsh, R.P.D., 2000. The erosional impact of soil hydrophobicity: Current problems and future research directions. Journal of Hydrology 231–232, 178–191.

Terry, J.P., Shakesby, R.A., 1993. Soil hydrophobicity effects on rainsplash: Simulated rainfall and photographic evidence. Earth Surface Processes and Landforms 18, 519–525.

Torri, D., Regues, D., Pellegrini, S., Bazzoffi, P., 1999. Within-storm soil surface dynamics and erosive effects of rainstorms CATENA 38 (2), 131–150.

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