# Temporal changes on the effect of rock fragments in interrill soil loss: a simulation experiment and a simple descriptive model

## Variação temporal do efeito da cobertura pedregosa na perda de solo por erosão interssulcos: simulação experimental e modelo descritivo

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### ABSTRACT

Soils with rock fragments have been studied under several aspects in the last years. Research shows that a single pattern in the erosional response of these soils to rainfalls is not always found.

In order to contribute to the understanding of this topic, an experiment was carried out, simulating interrill areas covered by rock fragments. This paper specifically aims at presenting and discussing temporal changes on sediment exported from such areas, also introducing a simple descriptive model to represent soil loss temporal evolution.

Small bottom perforated boxes, 612 $cm^2$ area, were filled with a silt-loam fine earth, very poor in organic matter, covered with simulated rock fragments and leaned at 10% slope gradient. The experiment comprised the exposure to 240 mm natural rainfall of 48 boxes corresponding to selected combinations, 4 replicates each, of rock fragments cover (0, 17, 30 and 66%), size (2, 4 and 10 cm), form (rectangular and circular) and position (resting on top and embedded). During the experiment boxes were kept under near saturation soil water conditions. Water and soil exported from the boxes as infiltration, runoff, wash and splash were measured after each period of precipitation.

Recorded values of soil loss plotted against precipitation, both expressed in cumulative terms, follow a sigmoid curve. This pattern of response was interpreted as a result of crust formation on soil surface exposed to rainfalls, a hypothesis suggested by observations during the experiment and confirmed at its end. Parameters of this model were related with rock cover and characteristics.

The effect of rock fragments on soil loss varies with time, a conclusion that must be taken into account when interpreting either results from experiments with different durations or the evolution of stoniness on eroding surfaces.

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## RESUMO

Os solos pedregosos vêm sendo estudados sob diversos aspectos nos últimos anos. No que respeita à perda de solo, os resultados publicados mostram todavia a dificuldade em estabelecer um padrão único de resposta destes solos às precipitações erosivas.

Com vista a aprofundar conhecimentos sobre este tópico, foi instalado um ensaio experimental, simulando superfícies com variável pedregosidade sujeitas a erosão interssulcos. Constitui objectivo deste trabalho apresentar e discutir a evolução temporal da perda de solo nessas superfícies, propondo a sua representação num modelo descritivo simples.

O ensaio compreendeu a exposição a 240 mm de chuva natural de um conjunto de tabuleiros com 612 $cm^2$ de área e 10% de declive, contendo terra fina franco-limosa, muito pobre em matéria orgânica, coberta por elementos grosseiros simulados. Os tabuleiros mantiveram-se próximo da saturação de água. Para além do solo nu, testaram-se tratamentos com 4 repetições cada, correspondendo a combinações específicas de 3 fracções de cobertura (17, 30 e 66%), 3 dimensões (2, 4 e 10 cm), 2 formas (rectangulares e circulares) e 3 posições (pousados à superfície, semi-aflorantes e aflorantes). A infiltração e o escoamento, e as perdas de solo neste e por salpico, foram medidas ao longo do ensaio, na sequência de períodos de precipitação.

A perda de solo acumulada representada em função da precipitação acumulada ao longo do ensaio segue uma curva sigmóide. Este modelo de resposta foi interpretado como resultando da formação da crosta superficial do solo exposto, hipótese sugerida pela observação no decorrer do ensaio e confirmada no final. Os parâmetros da curva sigmóide correlacionaram-se com a fracção de cobertura, tendo sido também explorada a relação com outros parâmetros descritivos da pedregosidade.

A conclusão de que a relação entre perda de solo e pedregosidade é temporalmente variável, traz consequências para a interpretação quer de resultados de ensaios com diferente duração, quer da evolução temporal da pedregosidade em superfícies erodidas.

## INTRODUCTION

Soils with rock fragments are common in large areas worldwide and, especially in the Mediterranean belt, they account for as much as 60% of the area (Poesen, 1990), a figure that points out their recognized relevance in this part of the world (Ibanéz *et al.*, 1996). Poesen (1990) also estimated that, for Portugal, 70% of the country area is covered by soils containing rock fragments. In NE Portugal, a regional area of 1.3 million ha, estimates based on soil survey data issued the following figures (Figueiredo, 2001): in 84% of the area soils have more 15% coarse elements and in 26% they have more than 20%; rock outcrops occur in 21% of the soil units mapped; soil phases related to the presence of rock fragments cover around 44% of the area; 34% of the area is stone covered.

Soils with rock fragments have been studied under several aspects in the last years (Poesen & Lavee, 1994). Specific research showed that a single pattern in the erosional response of these soils to rainfalls is sometimes not found. In fact, De Ploey (1981) noticed what he called the ambivalent effect of rock fragments on erosion; Lavee & Poesen (1991), with rainfall simulation, experimentally confirmed that observation for non-concentrated overland flow and interrill erosion. Regardless these important findings, research commonly outcomes a negative relationship between rock fragment cover and interrill runoff and soil loss (e. g., Figueiredo & Poesen, 1998; Poesen & Lavee, 1994), which is generally considered in erosion models (e. g., Flanagan, 1994; Renard *et al.*, 1996; Morgan *et al.*, 1998).

The contribution of features other than cover by rock fragments is not often addressed to in research on erosion and related processes. This was done, for example, by Poesen & Lavee (1991), Valentin & Casenave (1992), van Wesemael *et al.* (1996) and Cerdà (2001). As ranked by Figueiredo & Poesen (1998), for an experiment with simulated rock fragments, the relative contribution of size, position and form of rock fragments to explain losses due to wash and splash decreases from the first to the last. However, these authors found a strong interaction between the mentioned effects and this was later explained by Figueiredo (2001) and Figueiredo *et al.* (2004, in press) in terms of their composite contribution to the geometry of bare surfaces between rock fragments, from where sediment is removed by splash and wash.

The effects of rock fragment cover and characteristics are generally taken as static. However, Figueiredo & Poesen (1998) have shown that the relationship of rock fragment cover with splash and wash is variable in time. In line with the mentioned reference and specifically addressing to sediment export from interrill areas covered by rock fragments, this paper aims at introducing a simple descriptive model to represent soil loss time evolution.

## MATERIALS AND METHODS

### Simulation experiment

The experimental base for this work is thoroughly described in Figueiredo & Poesen (1998), a synthesis of which is presented below (see also Figure 1)

**Figure 1** – Experiment preparation and installation: top – preparing circular simulated rock fragments (lead pieces and melted paraffin) and filling soil boxes (boards are splash collectors); down – installing boxes outdoor (containers on the ground are infiltration collectors, boxes with cover plates are runoff / wash collectors)

TABLE 1 – **Treatments tested in simulation experiment (RC is Rock Fragment Cover)**

| **Treatment** | **RC (%)** | **Rock fragment axis size** | | | **Shape** | **Position** | **Material tested** [1] |
|---|---|---|---|---|---|---|---|
| | | **Longer** | **Intermediate** | **Shorter** | | | |
| 1 | 0 | - | - | - | - | - | Soil |
| 2 | 16.9 | 4.8 | 2.4 | 1.1 | Rectangular | On top | Soil |
| 3 | 30.1 | 4.8 | 2.4 | 1.1 | Rectangular | On top | Soil |
| 4 | 65.9 | 4.8 | 2.4 | 1.1 | Rectangular | On top | Soil |
| 5 | 30.4 | 2.2 | 1.2 | 1.1 | Rectangular | On top | Soil |
| 6 | 30.1 | 9.6 | 4.8 | 1.1 | Rectangular | On top | Soil |
| 7 | 28.7 | 2.0 | 2.0 | 1.1 | Circular | On top | Soil |
| 8 | 28.7 | 4.0 | 4.0 | 1.2 | Circular | On top | Soil |
| 9 | 30.1 | 4.8 | 2.4 | 1.1 | Rectangular | Half-Emb. | Soil |
| 10 | 30.1 | 4.8 | 2.4 | 1.1 | Rectangular | Embedded | Soil |
| 11 | 28.7 | 4.0 | 4.0 | 1.2 | Circular | Embedded | Soil |
| 12 | 30.1 | 4.8 | 2.4 | 1.1 | Rectangular | On top | Sand |

[1] Soil was a silt-loam fine earth (5% clay, 41% silt, 54% sand, 0.5% organic matter); Treatment 12, with sand as test material, was discarded from the analysis concerning this paper.

In order to simulate interrill areas, bottom perforated boxes with a surface of 612 cm$^2$ were filled with a silt-loam fine earth, very poor in organic matter, covered with simulated rock fragments and leaned at 10% slope gradient. The experiment comprised the exposure to 240 mm natural rainfall of 48 boxes corresponding to selected combinations, 4 replicates each, of rock fragments cover, size, form and position (Table 1). Soil water in boxes was kept near saturation. Water and soil exported from the boxes as infiltration, runoff, wash and splash were monitored during the experiment. Data base for this study consists on sediment losses by wash and splash measured at the end of each one of the 5 precipitation periods recorded.

## Model description

A model was designed for describing temporal evolution of soil losses due to splash and wash, taking into account experimental conditions. This is presented in the set of equations below and in Figure 2.

It is assumed that the bare soil surface is composed by a certain unknown amount of particles, available for wash and splash according to the competence of the respective erosive agents. Letting **q** be the amount of particles leaving the surface during time, **t**, and assuming that the rate of particle export is proportional to that amount, one has:

$$\frac{dq}{dt} = \alpha q \qquad \text{(eq. 1)},$$

The proportionality factor **α**, in turn, should be itself dependent on the amount **q** (eq. 2). In fact, the number of particles available for export should be limited, considering that: (i) these are the particles for which the agent is competent to promote their detachment and transport; (ii) agents in this processes act on the uppermost thin layer of the soil; (iii) size heterogeneity of particles remaining in the surface implies the need of increasingly higher competence of agents to remove them. Hence, as more particles leave the surface, lower should be the proportionality factor **α**, a statement that leads to the right hand part of eq. 2:

$$\alpha = f(q) = a - bq \qquad \text{(eq. 2)},$$

Eq. 2 incorporated in eq. 1 gives eq.3a, which may be written as in eq. 3b, introducing **K** as the ratio **a/b**:

$$\frac{dq}{dt} = a\left(1 - \frac{q}{a/b}\right)q \qquad \text{(eq. 3a)},$$

$$\frac{dq}{dt} = a\left(1 - \frac{q}{K}\right)q \qquad \text{(eq. 3b)}.$$

The integration of eq. 3b leads to the sigmoid curve represented in Figure 2 (Jolivet, 1983). In this curve some notable points must be highlighted, such as the minimum and maximum ordinates. The former should approach zero and the latter tends asymptotically to a maximum cumulative loss for which **dq/dt** approaches zero. The inflexion point of the sigmoid curve occurs for **K/2**, the corresponding abscissa being represented in Figure 2. It should be stressed that at inflexion point loss rates are the highest. Loss rates are similar at time zero and at a time twice as large as that for inflexion point. All these remarks are judged important for interpretations of results.

The model was applied for wash and splash, separately, taking cumulative soil loss as **q**, and cumulative precipitation as **t**, meaning that the independent variable is not time itself but the erosive agent effect during time. Non-linear regression tools of a statistical computer package were applied to fit the function described to data and estimate model parameters **K**, $\mathbf{q_0}$ and **a** (Wilkinson, 1989).

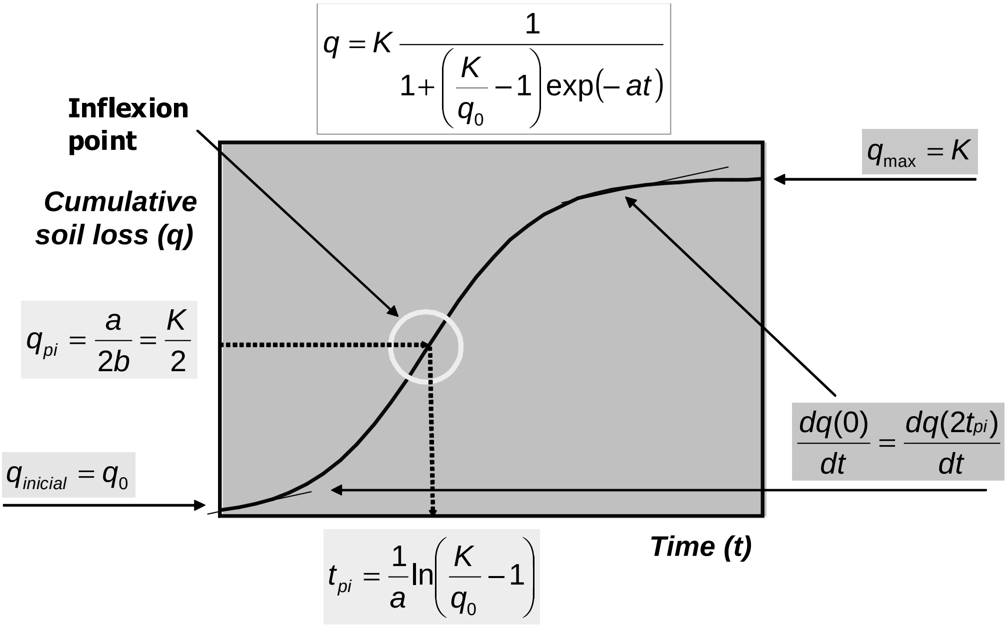

**Figure 2** – Model describing soil loss temporal evolution under tested conditions, q = f(t): sigmoid equation and its notable points (subscript "pi" means "at inflexion point")

## RESULTS AND DISCUSSION

Model sigmoid curves fit well recorded soil loss plotted against precipitation, both expressed in cumulative terms, although determination coefficients for splash were generally lower than those for wash (see $R^2$ corrected in Table 2). Furthermore, parameter estimation is consistent with model assumptions and data, either in the case of $\mathbf{q_0}$ (approaching zero in all treatments, especially for splash) or in that of **K** (close to final soil loss, yet with a slight underestimation; see last column of wash and splash blocks in Table 2).

For bare soil, the evolution of losses with time was linked to crust formation on the soil exposed to rainfalls, as suggested by changes observed in surface particle size (coarser) and cohesion (higher) (Figure 3). This was confirmed by results not presented here, of hydraulic conductivity measurements (falling head method) at the end of the experiment. Alexandre (1998), in simulated rainfall experiments, also found this pattern of soil loss temporal variation on bare soil.

Estimated model parameters (Table 2) were related with rock cover and characteristics. Figure 4 shows that rock cover affects the position of the inflexion point in the plot, lowering the correspondent ordinate, as expected, but increasing the abscissa. This result, together with the interpretation presented in the previous paragraph, indicate that rock cover tends to delay crust formation in the bare soil between rock fragments. Such effect was not as clear in splash as it was in wash (Figure 5).

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TABLE 2 – **Estimated parameters of model sigmoid curves for Treatments tested (CW and CSp are, respectively, cumulative wash and splash at the end of experiment)**

| **Treat** | **Wash** | | | | | **Splash** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **K** | $\mathbf{q_0}$ | **a** | $\mathbf{R^2}$ | **K /** | **K** | $\mathbf{q_0}$ | **a** | $\mathbf{R^2}$ | **K /** |
| | **g** $\mathbf{m^{-2}}$ | | $\mathbf{mm^{-1}}$ | **corr** | **CW** | **g** $\mathbf{m^{-2}}$ | | $\mathbf{mm^{-1}}$ | **corr** | **CSp** |
| 1 | 40.8 | 0.9 | 0.062 | 0.94 | 0.97 | 69.0 | 2E-05 | 0.190 | 0.72 | 0.98 |
| 2 | 30.7 | 0.7 | 0.058 | 0.95 | 0.96 | 47.0 | 4E-04 | 0.148 | 0.94 | 0.98 |
| 3 | 25.6 | 0.4 | 0.066 | 0.94 | 0.94 | 37.0 | 4E-04 | 0.143 | 0.82 | 0.92 |
| 4 | 5.7 | 0.0 | 0.126 | 0.92 | 0.67 | 17.7 | 2E-04 | 0.142 | 0.77 | 0.95 |
| 5 | 15.3 | 0.4 | 0.06 | 0.91 | 0.97 | 29.9 | 1E-03 | 0.127 | 0.91 | 0.96 |
| 6 | 20.1 | 0.7 | 0.057 | 0.96 | 0.96 | 36.1 | 3E-04 | 0.147 | 0.85 | 0.98 |
| 7 | 13.9 | 0.2 | 0.067 | 0.92 | 1.00 | 26.9 | 6E-03 | 0.106 | 0.79 | 0.94 |
| 8 | 19.4 | 0.1 | 0.077 | 0.93 | 0.97 | 36.1 | 5E-04 | 0.144 | 0.85 | 0.97 |
| 9 | 23.5 | 0.6 | 0.060 | 0.94 | 0.96 | 33.0 | 2E-04 | 0.152 | 0.93 | 0.97 |
| 10 | 24.2 | 0.7 | 0.057 | 0.80 | 0.96 | 38.4 | 8E-05 | 0.162 | 0.88 | 0.95 |
| 11 | 31.3 | 1.5 | 0.044 | 0.87 | 0.95 | 39.2 | 1E-04 | 0.158 | 0.93 | 0.94 |

**Figure 3** – Soil surface at the beginning of the experiment (left) and after 90 mm precipitation (right), for bare soil treatment (note the crusted surface)

Figueiredo (2001), based on geometrical considerations, devised a parameter for describing the tortuosity of runoff paths between rock fragments, which is directly dependent on rock fragment cover and characteristics. Tortuosity (**T**), as defined below, theoretically ranges from 0, in bare soil, to 1, in surfaces with extremely high rock fragment cover, both conditions being asymptotically approached, as stated in the following equations:

$$T = \frac{(1-RC)(b+db)}{d} \qquad \text{(eq. 4),}$$

$$d = \left(\frac{1}{\sqrt{RC}} - 1\right)\sqrt{a^2 + b^2} \qquad \text{(eq. 5),}$$

where **RC** is rock cover (0 – 1), **a** and **b** are larger and intermediate rock fragment axes, **da** and **db** are distances between rock fragments on **a** and **b** directions, respectively, and **d** is average global distance between rock fragments.

This index was calculated for all treatments but those with embedded rock fragments, and related to model parameters estimated with wash data. For all the three parameters (**K**, $\mathbf{q_0}$ and **a**), a linear trend prevailed and correlation coefficients were significant at 5% level (Figure 6). Nevertheless, best fit was obtained with **K** (final wash loss), with a determination coefficient, $R^2$, of 0.864. Apparently, initial loss ($\mathbf{q_0}$) is the main drawback of model parameters estimation, as the weak correlation between **T** and **a** seems to be due to a low range of variation in the latter parameter.

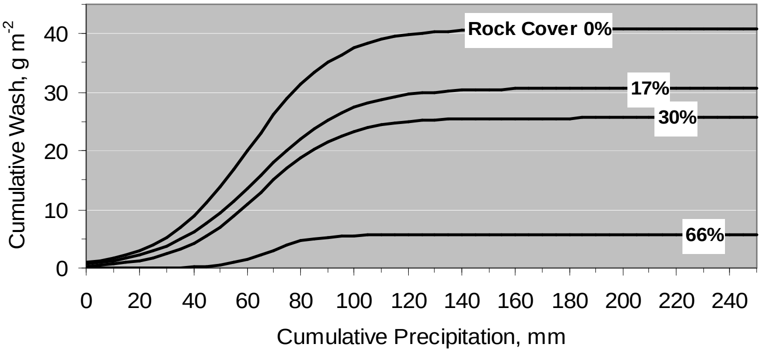

**Figure 4** – Temporal evolution of wash as affected by rock fragment cover: model outcome

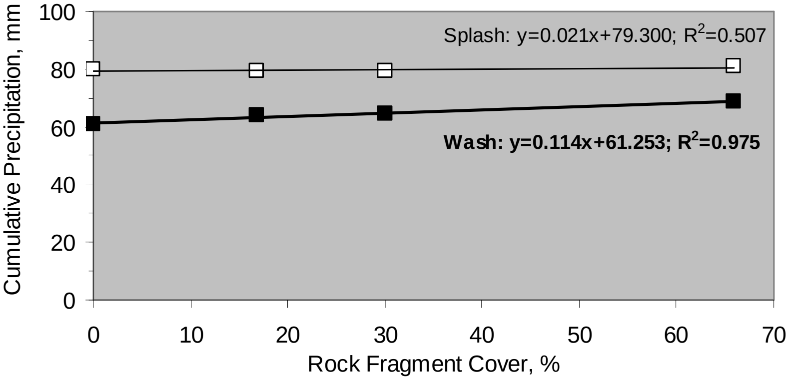

**Figure 5** – Effect of rock fragment cover on cumulative precipitation at inflexion point of model sigmoid curves fitted for wash (significant correlation) and splash (non-significant)

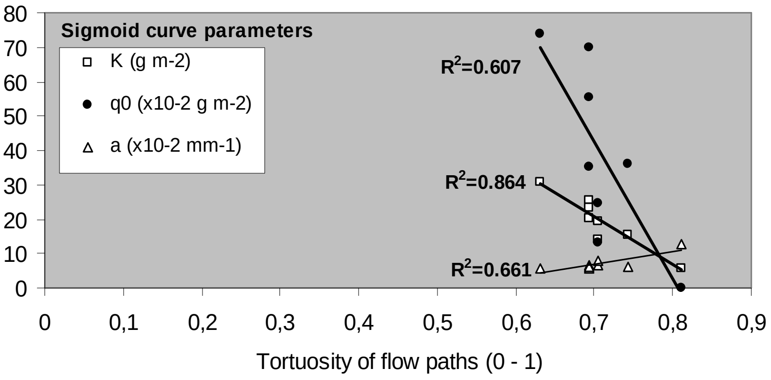

**Figure 6** – Correlation between model parameters (see Figure 2) and an index representing tortuosity of runoff paths (see eq. 4 and eq. 5)

## CONCLUSION AND CONSEQUENCES OF RESULTS

Due to a generally good agreement of model outcomes and data collected, it may be concluded that the model presented adequately describes temporal changes in soil loss by wash and splash from interrill areas covered with rock fragments. Correlation between model parameters and rock fragment cover and characteristics, although with differences in the goodness of fit, allows simulations on time evolution of eroding surfaces with variable stoniness.

This conclusion has important consequences for the interpretation of results from experiments concerning the effect of rock fragments on interrill soil loss, carried out with different durations. In fact, a large range of values was found by Poesen & Lavee (1994), in a thorough review of published data concerning the factor affecting rock cover percentage in the negative exponential relationship between wash loss and rock cover. Regardless other circumstances that might have affected experimental conditions under which data was obtained, it may be consistently hypothesized that the mentioned range is due to differences in experiment duration.

In view of illustrating this statement, model simulations were performed within the range of conditions tested. Simulation results show that, for a 30% cover by medium size rectangular rock fragments resting on top of soil surface, wash losses are about 40% of that in bare soil, if rains falling during the experiment account for 50 mm. In a longer experiment, for instance with 200 mm precipitation, wash losses would be 62% of those on bare soil.

Another consequence of results that should be highlighted, concerns the temporal evolution of interrill eroding/eroded surfaces where soils with rock fragments dominate. In fact, taking into account the sharp decline of sediment loss rates when cumulative precipitation is large, the erodibility of surfaces kept undisturbed for long may reach very low values. As so, at risk of large overestimation, prediction of time evolution of such surfaces should not be done on the base of erodibilities determined under short experimental periods, where much higher values are most probably found.

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