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Testing simple scaling in soil erosion processes at plot scale

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ABSTRACT

Explaining scale effects for runoff and erosion improves our understanding and simulation ability of hydrological and erosion processes. In this paper, plot scale effects on event runoff per unit area (Q_e), sediment concentration (C_e) and soil loss per unit area (SL_e) were checked at El Teularet-Sierra de Enguera experimental site in Eastern Spain. The measurements were carried out for 31 events occurring in the years 2005 and 2007 in bare ploughed plots ranging from 1 to 48 m^2. The analysis established the scaling relationship by dimensional analysis and self-similarity theory, and tested this relationship at different temporal scales ranging from event to annual scale. The dimensional analysis and the incomplete self-similarity condition allowed us to establish a power scaling relationship which was found to also be usable for the moments of k (1, 2, 3, 4) order. The power scaling relationship was theoretically deduced applying a boundary condition which is based on the hypothesis that sediment delivery processes do not occur at the selected plot scale. The simple scaling invariance condition was always verified (i.e. for each temporal horizon) for runoff and soil loss while the same hypothesis was not perfectly acceptable for sediment concentration. The analysis of the scaling relationships at event temporal scale showed that the spatial scale effects were less frequent for the composite variable (soil loss = sediment concentration × runoff) than the constituting variables. For 48% of the events, a statistically significant scale effect was detected for all tested variables. With reference to the statistically significant relationships, both runoff and soil loss always decreased and sediment concentration always increased in the passage from the reference area (1 m^2) to the largest one (48 m^2). The analysis at aggregated temporal scales suggested that annual scale effects for soil loss per unit area should be temporally more stable than those for both runoff and sediment concentration. Finally, at mean event scale the three investigated variables have a similar behaviour in terms of simple scaling invariance.

1. Introduction

Soil erosion is a key process to understand world land degradation, and understanding the soil erosion processes is necessary to reduce soil loss to sustainable values by proper restoration strategies (Di Stefano and Ferro, 2017; Keesstra et al., 2016a). Degraded soils are abundant on ecosystems where humans developed economic activities for millennia such as grazing, mining, agriculture (Larson et al., 1983), fires, abandonment or road construction as in the case of the Mediterranean (van Hall et al., 2016), although they are now also found in other areas of the world due to the acceleration of soil erosion rates and the abuse of soil resources (Trimble and Crosson, 2000; Keesstra et al., 2016b; Rodrigo-Comino and Cerdà, 2017).

Hydrological processes occur at a wide range of scales and many authors have recognized a scale dependency of these processes (Gentine et al., 2012; Cerdà et al., 2017; López-Vicente et al., 2015; Chen et al., 2016). According to Chen et al. (2016), in arid and semi-arid environments, hortonian runoff is a scaling process affected by rainfall, infiltration and runoff routing. Yair and Raz-Yassif (2004) suggested that short-term temporal variation in rain intensity and duration during

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a storm control the spatial distribution of the hillslope hydrological response. Other factors inducing scale effects are run-on processes (Corradini et al., 1998) and spatial variability of soil hydraulic properties (Li and Sivapalan, 2011) that can be altered by vegetation (Cerdà, 1997) and fauna (Cerdà and Jurgensen, 2011). However Wainwright et al. (2002) suggested that, even in the absence of spatial variability in infiltration, temporal variation in rainfall intensity is enough to induce scale dependency in runoff. Bagarello et al. (2011) noted that length effects on soil loss per unit area were small for highly erosive events and suggested that soil loss increases with plot length when rill erosion processes prevail. The scale effect studies did not paid attention to the landslides (De Sy et al., 2013), and lack of a multiscale approach to understand the whole geomorphological system (Ferrer et al., 2017) that will allow understanding the temporal and spatial sediment fluxes (Keesstra et al., 2014).

For scale dependency in soil erosion, Wilcox et al. (1997) noticed that the existence of hillslope sediment sinks was responsible of storing eroded sediments which is the notion encapsulated in the concept of sediment delivery rate (Ferro, 1997; Ferro and Porto, 2000). In addition, Rejman et al. (1999) argued that the scale dependency is explained taking into account that sediments collected from an erosion plot originate mainly from the plot area close to the outlet and not from all the plot (Parsons et al., 2006). Kidron (2011) confirmed the hypothesis that, in arid zones, contributing areas can be confined to a narrow belt at the bottom of the slope and scale effects are an inherent outcome of the intermittent character of the rain spells. Loch (1996) suggested three different erosion per unit area responses, corresponding to three different levels of rill network development (no rills, slight and strong rill development) with soil loss slightly to largely increasing with plot length. Masselink et al. (2017) found that agriculture land show a low connectivity between the slopes and the channels, which is also found in the forest land, where the connectivity is enhanced after forest fires (Cerdà and Doerr, 2010) due to the lack of vegetation. Yair and Raz-Yassif (2004) suggested that an inverse relationship between slope length and soil loss rate can be expected in arid environments due to both the concentration time required for continuous flow and the duration of the effective rainfall.

The comparability among the existing literature results is limited by the variability of the investigated plot lengths (0.2–72 m) (Rejman et al., 1999; Chaplot and Le Bissonnais, 2000; Joel et al., 2002; Rejman and Usowicz, 2002; Yair and Raz-Yassif, 2004; Rejman and Brodowski, 2005; Parsons et al., 2006; Bagarello and Ferro, 2004, 2010; Xu et al., 2009; Moreno-de las Heras et al., 2010; Bagarello et al., 2011; Thomaz and Vestena, 2012; Sadeghi et al., 2013) and the soil surface conditions, ranging from bare plots (Rejman et al., 1999; Rodrigo-Comino et al., 2017a, 2017b) to a stable vegetation cover (Moreno-de las Heras et al., 2010) or cropped conditions (Masselink et al., 2017).

The runoff scaling analyses reported in literature (Xu et al., 2009; Moreno-de las Heras et al., 2010) are based on experimental data and they highlight that an empirically deduced power law relationship can be used to describe scale effects. This relationship was recently positively tested by Chen et al. (2016) by a numerical investigation. The exponent of this power relationship, named *scaling exponent*, quantitatively expresses the scale effect.

The effect of temporal scale on erosion and deposition rates was examined by Peeters et al. (2008) which concluded that the measurements of current rates of soil erosion processes can be relevant for interpreting long-term landscape evolution.

The applicability of power scaling relationships was also tested by Hoffmann et al. (2013) with reference to the relationship between fine sediment storage S (10^9 kg) and basin area A (km^2):

$$S = a\left(\frac{A}{A_{ref}}\right)^b \tag{1}$$

in which b is the scaling exponent and a (10^9 kg) is the storage related to an arbitrarily chosen reference area. For a reference area equal to 10^3 km^2, which represents roughly the mean size of the available basins, Hoffmann et al. (2013) estimated by the usual regression techniques the a coefficient and the scaling exponent.

All proposed scaling relationship have generally a common empirical origin, i.e. are deduced fitting an equation to the available data pairs (for example area, measured soil loss). Even if the power equation was widely applied, different empirical relationships (e.g. linear or polynomial) have been used to check scale effects (Lal, 1997; Kinnell, 2008).

In a previous paper (Bagarello and Bagarello and Ferro, 2017), for the first time the scaling relationship was theoretically derived for the variable soil loss using the plot length as reference variable. This scaling relationship was then calibrated by 21 erosive events occurring at the experimental station for soil erosion measurements, Sparacia, Sicily, southern Italy. The developed analysis showed that rainfall characteristics did not explain the occurrence of significant scale effects nor were able to describe changes in the scaling exponent for sediment concentration and soil loss. In particular, events producing significant and non-significant effects on runoff and soil loss had similar single-storm erosion index and rainfall depth.

Bagarello and Bagarello and Ferro (2017) also highlighted that empirical data do not always yield a clear indication of the scale relationship that should be used. In other words, different empirical scaling equations can have a similar statistical performance. In particular, Bagarello and Bagarello and Ferro (2017) showed, as an example for a specific erosion event occurring at Sparacia experimental area, that the scale effect for runoff could be indifferently described by a linear or a power relationship. As a consequence, the scale effect becomes insignificant beyond a certain threshold value for a power scaling relationship while it remains significant for a linear relationship.

The main goal of this investigation was to demonstrate that, for a fixed scaling variable (plot length, area) defining the effect of the plot size on the variable representative of the studied phenomenon (runoff, soil loss), the theoretical derivation of the scaling relationship is independent of the availability of empirical data which are however necessary to calibrate the deduced relationship. In particular, the objective of the developed analysis was to check scale effects on runoff, sediment concentration and soil loss plot data collected at El Teularet Soil Erosion Research Station (Spain) on five plots of 1, 2, 4, 16 and 48 m^2. The specific goals were to: i) develop a theoretically based scaling relationship by dimensional analysis and self-similarity theory; ii) test the simple scaling invariance at event scale; and iii) check scaling relationships at different temporal scales (from event to annual scale).

2. Determining scale effects by dimensional analysis and self-similarity

For checking the scale effects the following power law can be considered:

$$\frac{y_A}{y_r} = \left(\frac{A}{A_r}\right)^m \tag{2}$$

in which y_A is the dependent variable (runoff, sediment concentration, soil loss) measured on the plot area A, y_r is the dependent variable measured on the reference plot having an area A_r (e.g. area equal to 1 m^2) and m is the *scaling* exponent.

Eq. (2) can be deduced using the dimensional analysis and the self-similarity theory (Bagarello and Bagarello and Ferro, 2017). According to Eq. (2), A_r is the area of the reference plot which is selected for scaling the dependent variable (runoff, sediment concentration, soil loss) values corresponding, for the same rainfall event and soil, to different plot sizes. In other words, the scaling relationship represented by