Influence of Topsoil Aggregate Stability on Runoff and Erosion

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Abstract: Estimating runoff and water erosion is expensive and time-consuming, but several authors have reported that these phenomena are linked to soil aggregate stability, whose determination is far easier. As this link had generally been deduced from rainfall simulations on sieved soil samples, our aim was to test its validity through field investigations. We determined susceptibility to runoff and erosion at three levels: through measurement of runoff and soil losses from 1m^2 microplots under simulated rainfall (Mediterranean highlands) and from 100 to 800m^2 runoff plots under natural rainfall (tropical areas), and finally, through semi-quantitative assessment of erosion feature frequency (Mediterranean hillsides). In each case, aggregate stability was determined by immersion in water and wet-sieving of 2mm sieved, air-dried 0 to 10cm soil samples. Runoff depths and soil losses from microplots and runoff plots, as well as the frequency index of erosion features on hillsides, were negatively correlated with topsoil stable macroaggregate (> 0.2 mm) content. As it greatly influences particle detachment by rainfall and seal formation, topsoil aggregate stability may thus be considered as an important determinant (and as a relevant indicator) of soil susceptibility to runoff and erosion, especially in Mediterranean and tropical areas, which undergo intense rainfall.

Keyword: erosion, runoff, erodibility, aggregate stability, slaking

1 Introduction

The evaluation of soil susceptibility to runoff and water erosion in the field is often expensive or time-consuming: evaluation at the catchment scale ($> 10^4$ m^2) often involves equipping the outlet to measure and sample runoff output; runoff plots (10—10^4 m^2) have to be fitted out with tanks, and measurements require long-term experiments to provide significant results; evaluation at the microplot scale (< 10 m^2) is generally achieved through rainfall simulation, which is a rather sophisticated method requiring large quantities of water. In addition, these evaluations require the presence of operators for long periods of time. Measurements of ^{137}Cs or magnetic susceptibility have been used to estimate soil redistribution in the landscape, but they also require sophisticated analyses and difficult calibrations (Sutherland, 1996; De Jong *et al*., 1998).

Due to these constraints, soil susceptibility to runoff and erosion, or soil erodibility, has been evaluated through laboratory tests on small soil samples (< 100 g), which are easy to implement and far less expensive and time-consuming than field-experiments. Among these laboratory tests, those relating to aggregate stability have received much attention. However, the relevance of aggregate stability as an erodibility indicator remains questionable, because it has generally been established through comparisons with runoff and soil loss measured during laboratory experiments, i.e. on sieved soil samples (Bryan, 1968; Reichert & Norton, 1994; Le Bissonnais & Arrouays, 1997), which behaviour is not always representative of field phenomena.

Our objective was to extend the validation of soil aggregation characterisation as a relevant method to evaluate soil susceptibility to runoff and water erosion. This was done through comparisons of topsoil aggregate stability and field-assessed susceptibility to runoff and erosion, which was determined at three levels: through measurements in microplots under simulated rainfall in a Mediterranean area, and on runoff plots in three tropical countries; and through the semi-quantitative assessment of the frequency of erosion features, on Mediterranean hillslopes.

2 Materials and methods (general information on sites is presented in Table 1)

2.1 Rainfall simulation on microplots (barthès *et al*., 1999)

Rainfall simulation tests were carried out in Montlaur (southern France), on seven 18 m× 9 m plots with a slope of 5%—12%, mechanically cropped with spring-oats. The experiment involved several types of tillage and inputs. Simulated rainfall was produced by a nozzle mounted on a 4-m high tower, and was applied to a 1 m×1 m microplot. Prior to the rainfall application, microplot vegetation was uprooted and the soil was manually tilled, leading to similar roughness in all plots. Rainfall at 60 mm • h^{-1} was applied to each experimental plot, beginning with dry soil and continuing until runoff steady state was achieved. Undisturbed 0—10 cm soil samples were collected close to each microplot.

Table 1 Main characteristics of the experimental situations

Location	Scale	Climate, annual rainfall and temperature	Altitude	Geology	Soil type (FAO), topsoil texture
Montlaur, France, 44°N, 3°E	1 m²	Mediterranean, 800 mm, 12°C	400 m	Schist, claystone	Dystric Regosol, 30% clay, 30% sand
Agonkanmey, Benin, 6°N, 2°E	240 m²	Subhumid-tropical, 1200 mm, 27°C	20 m	Sandstone	Dystric Nitosol, 10%—20% clay, 70%—80% sand
Mbissiri, Cameroon, 8°N, 15°E	100 m²	Subhumid-tropical, 1300 mm, 26°C	370 m	Ferrugineous sandstone	Orthic Ferralsol, 5%—10% clay, 80%—90% sand
S.M. Tlaixpan, Mexico, 20°N, 99°W	800 m²	Subhumid-temperate, 700 mm, 13°C	2600 m	Tuff	Eutric Regosol, 25%—30% clay, 30%—40% sand
Hassakeh, Syria, 37°N, 41°E	40 m²	Subtropical semiarid, Mediterranean, 300 mm, 16°C	500—800 m	Limestone, marl, dolomite	Calcaric Regosol, Calcic Cambisol, 40%—45% clay, 15%—25% sand
Limoux, France, 43°N, 2°E	1 to 20 ha	Mediterranean, 600-800 mm, 13—14°C	100—400 m	Molasses, pudding-stones, conglomerates, limestones, marls	Cambisols and Regosols with various textures

2.2 Runoff plots in benin, cameroon, mexico (barthès et al., 2000) and syria (shinjo *et al*., 2000)

Runoff plots were set up in Agonkanmey (Benin), Mbissiri (Cameroon), and San Miguel Tlaixpan (Mexico). At Agonkanmey (Benin), the study was carried out on four 30 m× 8 m runoff plots (4% slope), with one cultivation treatment per plot: maize with or without fertilizers, and intercropping maize-legume cover crop every year or one year out of two, in each case with hoe cultivation. At Mbissiri (Cameroon), the study was carried out on five 20 m× 5 m runoff plots (1 to 2.5% slope), with one treatment per plot: savanna, ploughing with residue removal or spreading on an old clearing, and ploughing with residue removal or direct drilling on a recent clearing. During the three years under study, the cultivated plots were cropped in cotton, maize then cotton, and involved mechanized mounding and fertilizers. At San Miguel Tlaixpan (Mexico), the experimental plots were set up on material resulting from 40-cm deep subsoiling, terracing, mouldboard ploughing then twofold disc-harrowing of an outcropping indurated horizon, called tepetate. The study was carried out on five 40 m× 20 m runoff plots (2.5 to 4.7% slope), with one treatment per plot: the reference plot was under fertilized cereal-legume mixed cropping, and the other plots differed from the reference one in fourfold disc-harrowing, cereal monocropping, manure instead of fertilizers, and 60cm deep subsoiling, respectively. Over the three years under study, mean rainfall erosion index (Wischmeier & Smith, 1978) reached 10,688, 9907 and 1683 MJ mm • (ha • h)$^{-1}$ at Agonkanmey, Mbissiri and San Miguel Tlaixpan, respectively. In each of the 14 runoff plots, composite soil samples were collected at a 0—10 cm depth, towards the end of the studies. We completed our results with those from Shinjo *et al*. (2000), relating to six 21 × 1.8 m runoff plots (3 to 19% slope) near Hassakeh (Syria). They were mainly under herbaceous and shrub vegetation and either grazed or preserved from grazing, with an additional tilled fallow. The mean rainfall erosion index was 215 MJ mm • (ha • h)$^{-1}$.

2.3 Semi-quantitative assessment of erosion features on hillsides (guichou, 1998)

We studied eight hillsides in the Limoux vineyard (southern France), with slopes often reaching 20%. Each hillside was divided into functional segments having homogeneous slope, topsoil and geological substratum. Altogether 23 segments were identified for the eight hillsides. The frequency of each type of erosion feature was assessed semi-quantitatively on three perpendicular-to-the-slope 10m transects per functional segment, and marked from 0 (absence) to 4 (omnipresence): these erosion features were sedimentation crusts (whose frequency was denoted a_1), stones on the soil surface (a_2), small pedestals (a_3), microcliffs (a_4), grooves (b), rills (c) and gullies (d). The erosion index was defined as:

$$\text{erosion index} = a_1 + a_2 + a_3 + a_4 + 2b + 3c + 4d \tag{1}$$

This erosion index was averaged over the three transects of each functional segment. Erosion features were not visible on plots which had been tilled a few days before observations were made; the erosion index was thus determined on the 17 remaining segments. In addition, composite soil samples were collected on each functional segment at a depth of 0—10 cm.

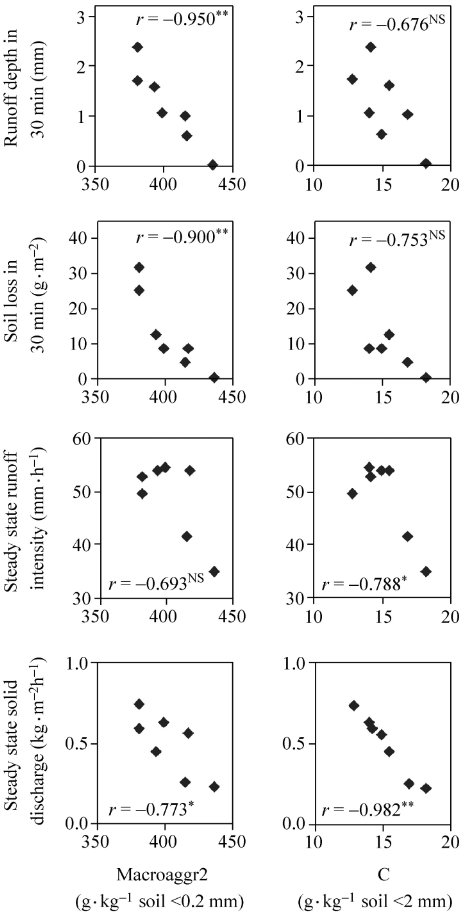

Fig.1 Relationships between runoff or erosion parameters under simulated rainfall, and topsoil(0—10cm) contents in stable macroaggregates (> 0.2 mm) or total carbon C, in a southern France Regosol.

2.4 Analyses

Water-stability of aggregates was determined on 2mm sieved air-dried soil samples of 4 g, using a test adapted from Kemper & Rosenau (1986). Each sample was immersed in deionized water then wet-sieved using 0.2mm sieves. The fraction < 0.2 mm was collected to determine fraction < 0.02 mm, denoted microaggregate fraction (Microaggr1), by the pipette method. The fraction > 0.2 mm was sieved into dispersive solution, using the same 0.2mm sieves, in order to determine coarse sand content. Macroaggregate (> 0.2 mm) and mesoaggregate (0.02—0.2 mm) fractions (Macroaggr1 and Mesoaggr1) were defined as follows:

$$\text{Macroaggr1} = \text{Fraction} > 0.2 - \text{Coarse sands} \tag{2}$$

$$\text{Mesoaggr1} = 1000 - \text{Coarse sands} - \text{Macroaggr1} - \text{Microaggr1}. \tag{3}$$

These fractions were expressed in g • kg^{-1} soil < 2 mm. Macro-, meso- and microaggregate fractions were also determined on a basis free of coarse sand (Macroaggr2, Mesoaggr2 and Microaggr2, respectively), e.g.:

$$\text{Macroaggr2} = 1000\ \text{Macroaggr1} / (1000 - \text{Coarse sands}), \tag{4}$$

with Macroaggr2 + Mesoaggr2 + Microaggr2 = 1000 g • kg^{-1} soil < 0.2 mm. Total carbon content of soil samples was determined by dry combustion. Determination of aggregate stability in the Syrian experiment (Shinjo *et al.*, 2000) differed from ours in the following ways: soil sampling depth ranged from 3 to 11 cm; only 1—2 mm dry aggregates were tested.

Correlation coefficients (r) significant at $p < 0.05$ and $p < 0.01$ were denoted * and **, respectively, whereas non significant ones were denoted ^{NS}.

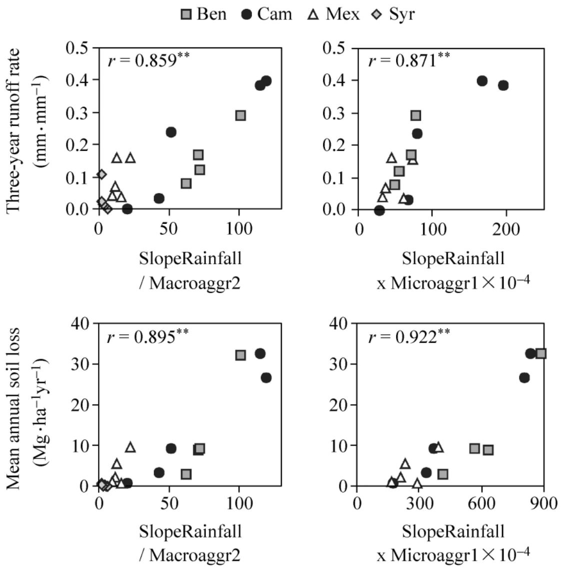

Fig.2 Relationships between three-year runoff rate or mean annual soil loss and topsoil (0—10 cm) aggregation and environment parameters, in runoff plots from Benin, Cameroon, Mexico and Syria (Macroaggr2 > 0.2 mm in Benin, Cameroon and Mexico, > 0.25 mm in Syria, in g • kg^{-1} soil < 0.2 mm; Microaggr1 < 0.02 mm and 0.02 < Mesoaggr1 < 0.2 mm, in g • kg^{-1} soil < 2 mm; SlopeRainfall = slope gradient × mean rainfall erosion index, in % and MJ mm • ha^{-1} • h^{-1}, respectively).

3 Results

3.1 Rainfall simulation on microplots in southern france (Fig.1)

Runoff depth and soil loss during the initial 30 min of rainfall were significantly and negatively correlated with Macroaggr1 (r=–0.937** and r=–0.811*, respectively) and Macroaggr2 (r=–0.950** and r=–0.900**, respectively), but not with C ($r \geqslant -0.753^{NS}$). During runoff steady state, runoff intensity and solid discharge were correlated with C (r=–0.788* and r=–0.982**, respectively), but solid discharge only was correlated with Macroaggr2 (r=–0.773*). Runoff and erosion were thus closely linked (i) with topsoil macroaggregate stability during the first part of the rainfall, and (ii) with C, and to a lesser extent, with macroaggregate stability, during the second part of the rainfall (however, 30-min rainfall at 60mm • h^{-1} occurs every ten years in this region).

3.2 Runoff plots in benin, cameroon, mexico and syria (Fig. 2)

Mean annual runoff rate and soil loss from the runoff plots were significantly correlated with Macroaggr1 and Macroaggr2 (–0.73**< r < –0.62**), with their inverse functions 1/Macroaggr1 and 1/Macroaggr2 (0.73**< r < 0.84**), with Mesoaggr2 (0.68**< r < 0.73**), but not with the other aggregation parameters or C ($|r| < 0.5^{NS}$). Moreover, mean annual runoff rate and soil loss were significantly correlated with the product of a SlopeRainfall factor (which was defined as the product of slope gradient by mean rainfall erosion index) by 1/Macroaggr2, Mesoaggr1, Microaggr1, Microaggr2 or 1/C (0.81**< r < 0.93**). Runoff and erosion measured on runoff plots were thus closely linked with topsoil aggregate stability; correlations were improved when considering slope gradient and rainfall aggressiveness in addition to aggregate stability.

3.3 Semi-quantitative assessment of erosion features on hillsides (Fig. 3)

Within the population formed by the 17 functional segments where the frequency of erosion features was assessed, there were significant correlations between the semi-quantitative erosion index and Macroaggr1 (r=–0.584*) or Macroaggr2 (r=–0.634**). Correlations were closer (r=-0.855** and r=–0.924**, respectively) within the 11 segments with no conservation practices (e.g. ditches, grass strips) than within the former population, erosion being more directly related to soil aggregation in the absence of such practices.

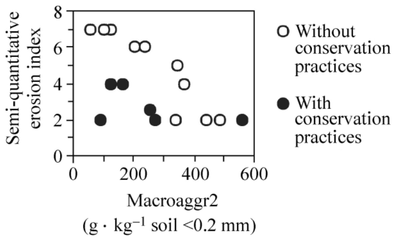

Fig.3 Relationship between the semi-quantitative erosion index and topsoil (0—10 cm) content in stable macroaggregates (the erosion index is the sum of the weighted frequencies of erosion features observed on the hillsides).

4 Discussion and conclusion

Many authors have reported negative relationships between aggregate stability and soil susceptibility to runoff and erosion (Bryan, 1968; Reichert & Norton, 1994; Le Bissonnais & Arrouays, 1997). However, this susceptibility was generally assessed through rainfall simulations on rehandled and sieved soil samples, whose behaviour is not always representative of phenomena occurring in the field. Some authors have also reported relationships between aggregate stability and soil susceptibility to erosion from field experiments, but each study referred to a limited number of soil types (Quantin & Combeau, 1962; Roth et al., 1987; Valentin & Janeau, 1989). Our results confirmed that aggregate stability was closely and negatively related to soil susceptibility to runoff and erosion investigated in the field at different scales, in different locations and contexts, and using different methods.

More precisely, our results showed that soil susceptibility to runoff and erosion was linked to topsoil aggregate resistance to slaking: indeed, slaking results from the compression of air entrapped inside rapidly wetted aggregates, and it is the main mechanism causing aggregates to disintegrate when dry soil is immersed (Le Bissonnais, 1996; Fox & Le Bissonnais, 1998), as was the case in our studies. Other mechanisms than slaking may determine aggregate breakdown. However, several studies indicate that for most soils, the wetting rate is of greater importance than drop impact as a factor in aggregate breakdown on wetting (Loch & Foley, 1994; Morin & Van Winkel, 1996). Slaking may thus be considered as particularly important in aggregate disintegration, especially (i) in tropical or Mediterranean areas, where intense rainfall is frequent, and (ii) in soils with low exchangeable sodium proportion (ESP) and swelling clay content, as was the case in our studies.

Aggregate disintegration is not the only mechanism involved in erosion. However, it greatly influences soil detachment by rainfall, which is recognized as the dominant erosive force affecting erosion rate in interrill areas, where transport capacity is generally not acknowledged as a limiting factor (Poesen, 1992; Jayawardena & Bhuiyan, 1999). Indeed, the water-stability of macroaggregates is known to prevent detachment of easily transportable particles, and thereby surface clogging and runoff (Le Bissonnais, 1996). Moreover, it has been suggested that the rate of aggregate disintegration determined the rate of seal formation (Shainberg et al., 1997), which is closely linked with the potential for rilling (Poesen, 1992); consequently topsoil aggregate stability may also be considered an important determinant of rill erosion. Thus the influence of topsoil aggregate resistance to slaking on interrill and rill erosion explains the relationships between aggregate stability and susceptibility to runoff and erosion, especially on low-ESP non-swelling soils that are subject to intense rainfall.

Limited capacity of soil moisture storage is a possible cause of erosion (Roose, 1996; Van Dijk & Kwaad, 1996). However, considering the link between aggregate stability and susceptibility to runoff and erosion, it is likely that our experiments involved infiltration-excess rather than saturation-excess overland flow.

In our studies, considering rainfall aggressiveness, slope and the existence of conservation practices in addition to topsoil aggregation resulted in better relationships with soil susceptibility to runoff and erosion than only considering aggregation. The Universal Soil Loss Equation relates erosion to rainfall aggressiveness, soil erodibility, slope, cover and management, and conservation practices (Wischmeier & Smith, 1978); for erosion modelling purposes, it might thus be suitable to express soil erodibility through topsoil aggregate stability.

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