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Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels

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Abstract

The evaluation of soil susceptibility to runoff and water erosion in the field is often expensive or time-consuming. Several authors have reported that susceptibility is linked to aggregate stability, whose determination is far easier. However, this susceptibility has generally been deduced from rainfall simulation experiments on sieved soil samples, whose behaviour is not always representative of field-scale phenomena. Our aim was to extend the validity of relationships between soil aggregation and erosion through comparisons of topsoil aggregate stability and field-assessed susceptibility to runoff and erosion.

Susceptibility to runoff and erosion was determined at several levels: first, on a southern French Regosol, through measurements of runoff and soil loss from 1-m^2 microplots under simulated rainfall; second, from 100- to 800-m^2 runoff plots on a Nitosol in Benin, a Ferralsol in Cameroon and a Regosol in Mexico (with additional data on Syria from the literature); and finally, soil susceptibility to erosion was determined through semi-quantitative assessment of the frequency of erosion features on vineyard hillsides in southern France. Aggregate stability was determined by immersion in water and wet-sieving of 2-mm sieved, air-dried 0- to 10-cm soil samples, which actually tests aggregate resistance to slaking.

Under simulated rainfall, runoff depth and soil loss after 30 min were negatively correlated with topsoil content in stable macroaggregates (>0.2 mm). On runoff plots, 3-year runoff rate and soil loss were negatively correlated with topsoil aggregate stability, especially stable macroaggregate content; these correlations were improved when slope gradient and climate aggressiveness were considered in addition to aggregate stability. On vineyard hillsides, the frequency index of erosion features was negatively correlated with topsoil content in stable macroaggregates, especially in the absence of conservation practices.

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These results confirm that aggregate stability is a relevant indicator of soil susceptibility to runoff and erosion, especially in Mediterranean and tropical areas where intense rainfall is frequent. They also confirm that simple laboratory determination can provide data closely correlated with those resulting from field investigations. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Erosion; Runoff; Erodibility; Aggregate stability; Slaking

1. Introduction

Soil erosion caused by water is primarily due to particle detachment and transport by rainfall and runoff (Ellison, 1947). This type of erosion is referred to as interrill erosion when detachment and transport are caused by raindrops and shallow surface flow, and as rill erosion when they are caused by runoff concentrated into discernible channels (Jayawardena and Bhuiyan, 1999). The evaluation of soil susceptibility to runoff and water erosion in the field is often expensive or time-consuming. Runoff and soil loss may be assessed at different scales: catchment ($>10^4$ m^2), plot ($10-10^4$ m^2) or microplot (<10 m^2) (Mutchler et al., 1988; Hudson, 1993). At the catchment scale, evaluation often involves equipping the outlet to measure and sample runoff output, implying either the use of sophisticated equipment or the presence of operators. Similarly, runoff plots have to be fitted out with tanks, and the measurement of collected runoff and sediments also requires operators or expensive equipment. Moreover, these evaluations are made under natural rainfall, and to provide significant results they generally require long-term experiments, i.e. a minimum of 3 years. At the microplot scale, evaluation of runoff and soil loss often involves rainfall simulation, which is a rather sophisticated method requiring several operators over a period of several days as well as large quantities of water with low electrolyte concentration. Other methods such as ^{137}Cs counting and measurement of magnetic susceptibility have also been used to estimate soil redistribution in the landscape. However, in addition to the need for sophisticated analyses, they provide pluri-decennial balances of soil movements, which are not the most suitable for assessing water erosion and the effects of some of its determinants (e.g., cropping systems). Moreover, variability in ^{137}Cs counting from non-eroded references remains an important concern as regards the first method, as well as variability in parent materials (with different magnetic properties) regarding the second one (Sutherland, 1996; De Jong et al., 1998).

Due to these constraints, soil susceptibility to runoff and erosion, or soil erodibility, has also 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: (i) relevance has generally been established through comparisons with runoff and soil loss measured under simulated rainfall during laboratory experiments, i.e. on rehandled and sieved soil samples (Bryan, 1968; Luk, 1977; Reichert and Norton, 1994; Amezketa et al., 1996; Le Bissonnais and Arrouays, 1997); (ii) the behaviour of sieved, rehandled samples is not always representative of field phenomena.

The objective of our work was to extend the validation of soil aggregation characterisation as a simple and 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. Aggregate stability was determined through immersion and subsequent wet-sieving of < 2-mm air-dried soil samples into water, which actually tests aggregate resistance to slaking (Le Bissonnais, 1996). Susceptibility to runoff and erosion was determined at three levels: first through measurements of runoff and soil loss from microplots (1 m^2) under simulated rainfall in a southern French Regosol; second through 3-year measurements of runoff and soil loss on runoff plots (100–800 m^2) in Benin, Cameroon and Mexico, with additional data on Syria from the literature; and lastly, soil susceptibility to erosion was determined through the semi-quantitative assessment of the frequency of erosion features, on vineyard hillslopes in southern France.

2. Materials and methods

Information on the location, climate, geology and soils of the experimental sites is presented in Table 1.

2.1. Rainfall simulation on microplots in Aveyron, southern France (Barthès et al., 1998, 1999)

Rainfall simulation tests were carried out in Montlaur, in the Department of Aveyron, in southern France. The experimental plots were located on the upper part of a hill with a slope of 5–12%. The experimental design included seven 18 × 9 m plots mechanically cropped with spring oats: flat mouldboard ploughing, raised mouldboard ploughing and superficial tillage with either mineral fertilizers or sheep manure, and direct drilling with sheep manure only. Soil sampling and rainfall simulation were done 10 weeks after seeding. Rainfall simulation was carried out with an ORSTOM device (Asseline and Valentin, 1978). Rainfall was produced by a nozzle mounted on a 4-m high tower, and was applied to a 1 × 1 m microplot surrounded by a half-buried frame with an opening at the lower side to collect runoff. Prior to the rainfall application, microplot vegetation was uprooted and the top 15 cm of the soil was manually tilled, in order to obtain 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. Runoff intensity and solid discharge were measured by means of periodical runoff sampling, and these values were cumulated to calculate runoff depth and soil loss, respectively. Undisturbed 0–10 cm soil samples were collected close to each microplot.

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 (southern Benin), Mbissiri (northern Cameroon), and San Miguel Tlaixpan (central Mexico).

At Agonkanmey (Benin), the study was carried out on four 30 × 8 m runoff plots with 4% slope, with one cultivation treatment tested in each plot: pure maize cropping system with or without mineral fertilization, and intercropping of maize and a legume cover crop

Table 1
Main characteristics of the experimental situations

Location	Scale	Climate	Mean annual rainfall and temperature	Altitude	Geological substratum	Soil type (FAO)	Topsoil clay and sand contents
Montlaur (Aveyron), southern France 43°53′ N, 2°49′ E	Microplots (1 m^2)	Mediterranean (continental and oceanic influences)	ca. 800 mm and 12 °C	ca. 400 m	Schist, claystone	Dystric Regosol	ca. 30% clay and 30% sand
Agonkanmey, southern Benin 6°24′ N, 2°20′ E	Plots (240 m^2)	Subhumid-tropical (two rainy seasons)	ca. 1200 mm and 27 °C	ca. 20 m	Sandstone	Dystric Nitosol	ca. 10–20% clay and 70–80% sand
Mbissiri, northern Cameroon 8°23′ N, 14°33′ E	Plots (100 m^2)	Subhumid-tropical (one rainy season)	ca. 1300 mm and 26 °C	ca. 370 m	Ferrugineous sandstone	Orthic Ferralsol	5–10% clay and 80–90% sand
San Miguel Tlaixpan, central Mexico 19°30′ N, 98°48′ W	Plots (ca. 800 m^2)	Subhumid-temperate (marked dry season)	ca. 700 mm and 13 °C	ca. 2600 m	Tuff	Eutric Regosol	25–30% clay and 30–40% sand
Hassakeh, northeastern Syria 36°30′ N, 40°30′ E	Plots (ca. 40 m^2)	Subtropical semiarid Mediterranean	ca. 300 mm and 16 °C	500–800 m	Limestone, marl, dolomite	Calcaric Regosol, Calcic Cambisol	40–45% clay and 15–25% sand
Limoux (Aude), southern France 43°04′ N, 2°12′ E	Hillsides (1–20 ha)	Mediterranean (mountainous and oceanic influences)	600–800 mm and 13–14 °C	100–400 m	Molasses, pudding-stones, conglomerates, limestones, marls, sandstones	Cambisols and Regosols	Variable (from sandy to clayey texture)

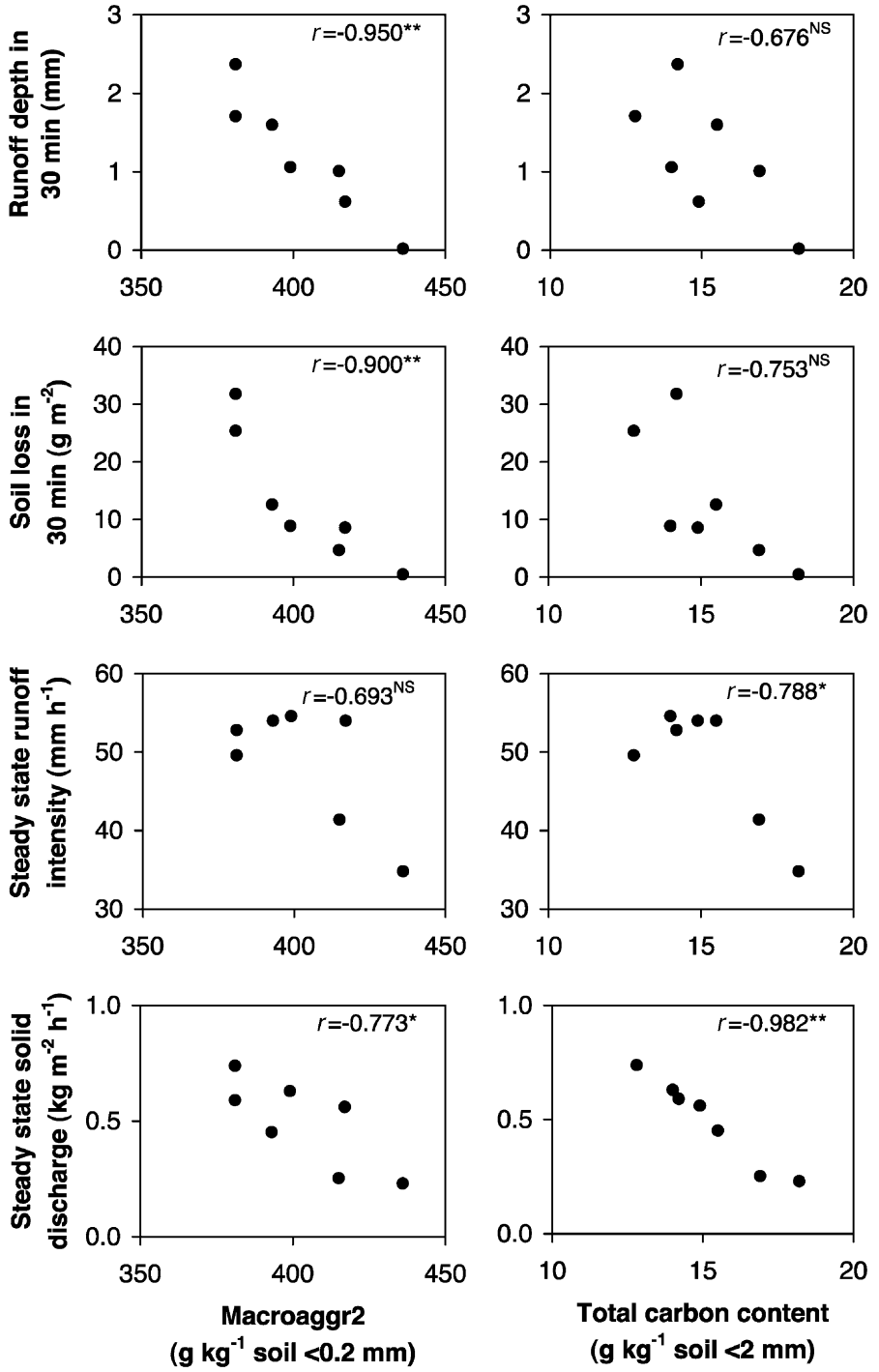
(*Mucuna pruriens* var. *utilis*) every year or 1 year out of 2 (with pure maize cropping during the second year), in each case with superficial hoe cultivation. Current experimentation began in 1988, but our study is concerned only with the years 1995–1997. Annual rainfall reached 1000, 1126 and 1558 mm in 1995, 1996 and 1997, respectively, and the rainfall erosion index reached 8762, 9768 and 13,516 MJ mm (ha h)$^{-1}$, respectively, i.e. an average of 10,688 (following Wischmeier and Smith, 1978, this index was determined by adding, over a period of 1 year, the products of the energy of each rainstorm multiplied by its maximum 30-min intensity).

At Mbissiri (Cameroon), the study was carried out on five 20 × 5 m runoff plots, with one treatment per plot: savanna (1% slope), mouldboard ploughing on a 30-year-old clearing with either residue removal or spreading (2.5% slope), and either mouldboard ploughing with residue removal or direct drilling on a 1991 clearing (2% slope). The four cultivated plots were cropped in maize (1991, 1993) and cotton (1992, 1994), and involved mechanized mounding with the rows parallel to the slope, and mineral fertilization. Experimentation began in 1991, but our study is concerned only with the years 1992–1994. Annual rainfall reached 1511, 1072 and 1353 mm in 1992, 1993 and 1994, respectively, and the rainfall erosion index registered 13,620, 8606 and 7513 MJ mm (ha h)$^{-1}$, respectively, i.e. an average of 9907.

At San Miguel Tlaixpan (Mexico), the experimental plots were set up on material resulting from splitting up and loosening of an outcropping indurated horizon, called tepetate. Cultivation of the tepetate involved 40-cm deep subsoiling, terracing, mouldboard ploughing then twofold disc-harrowing. The study was carried out on five 40 × 20 m runoff plots, with one treatment per plot: the reference plot (4.4% slope) was under cereal-legume mixed cropping with mineral fertilization; the other plots differed from the reference one in fourfold disc-harrowing (second plot, 2.5% slope), monocropping of cereals (third plot, 3.2% slope), manure application instead of mineral fertilization (fourth plot, 3.4% slope), and 60-cm deep subsoiling (fifth plot, 4.7% slope). Experimentation began in 1993 and our study is concerned with the years 1993–1995. Annual rainfall reached 411, 736 and 768 mm in 1993, 1994 and 1995, respectively, and rainfall erosion index registered 954, 2151 and 1961 MJ mm (ha h)$^{-1}$, respectively, i.e. an average of 1683.

All 14 runoff plots were surrounded by half-buried sheets and fitted out with collectors draining runoff and sediments toward tanks set up in series. The runoff amount was assessed on every plot after each rainfall event by measuring the volume of water in each tank and multiplying it by a coefficient depending on divisors. Runoff depth was calculated by dividing the runoff amount by the plot area; annual runoff rate was defined as the ratio of annual runoff depth to annual precipitation, and 3-year runoff rate as the ratio of 3-year runoff depth to 3-year precipitation. Wet coarse sediments were collected at the bottom of the first tank and weighed; dry coarse sediment amount was determined after oven-drying of the whole or of aliquots. Quantities of suspended sediment were assessed by flocculation and oven-drying of aliquots collected in the tanks. Annual soil loss was defined as the sum of dry-coarse and -suspended sediment amounts over 1 year; its average over 3 years was denoted mean annual soil loss. Composite soil samples were collected on each plot at a 0- to 10-cm depth, towards the end of the studies.

We completed our results with those from Shinjo et al. (2000), relating to six runoff plots near Hassakeh, in northeastern Syria. The plots covered 21 × 1.8 m and had slopes


Runoff depth in 30 min (mm)
Soil loss in 30 min (g m-2)
Steady state runoff intensity (mm h-1)
Steady state solid discharge (kg m-2 h-1)
r=-0.950**
r=-0.676NS
r=-0.900**
r=-0.753NS
r=-0.693NS
r=-0.788*
r=-0.773*
r=-0.982**
Macroaggr2 (g kg-1 soil <0.2 mm)
Total carbon content (g kg-1 soil <2 mm)

ranging from 3% to 19%. They were mainly under herbaceous and shrub vegetation and either extensively grazed as natural rangeland or preserved from grazing, with an additional tilled fallow. The average rainfall erosion index was 215 MJ mm (ha h)$^{-1}$. Equipment and measurements were similar to those used in Benin, Cameroon and Mexico.

Although these 20 runoff plots represented a wide range of cropping systems and soil and climate conditions, the variations in slope gradient (generally $<5\%$), length (from 20 to 40 m) and vegetation cover (mainly herbaceous) between plots were generally rather low.

2.3. Semi-quantitative assessment of erosion features on hillsides in Aude, southern France (Guichou, 1998)

The Limoux vineyard is located on the hillsides of the Pyrenean piedmont, in the Department of Aude, in southern France. Eight hillsides were studied, each covering between 1 and 20 ha, with slopes often reaching 20% under cultivation. Each hillside was divided into functional segments with homogeneous slope (shape, gradient), topsoil (colour, texture, stoniness) and geological substratum, which were briefly characterised in the field; land use, direction of the vineyard rows and conservation practices, such as ditches and grass strips, were also noted. 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 10-m 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), related to sheet erosion, and grooves (whose frequency was denoted b), rills (c) and gullies (d), related to linear erosion (grooves, rills and gullies were defined by their depth, which was <10, 10–30 and >30 cm, respectively). The erosion index was defined as:

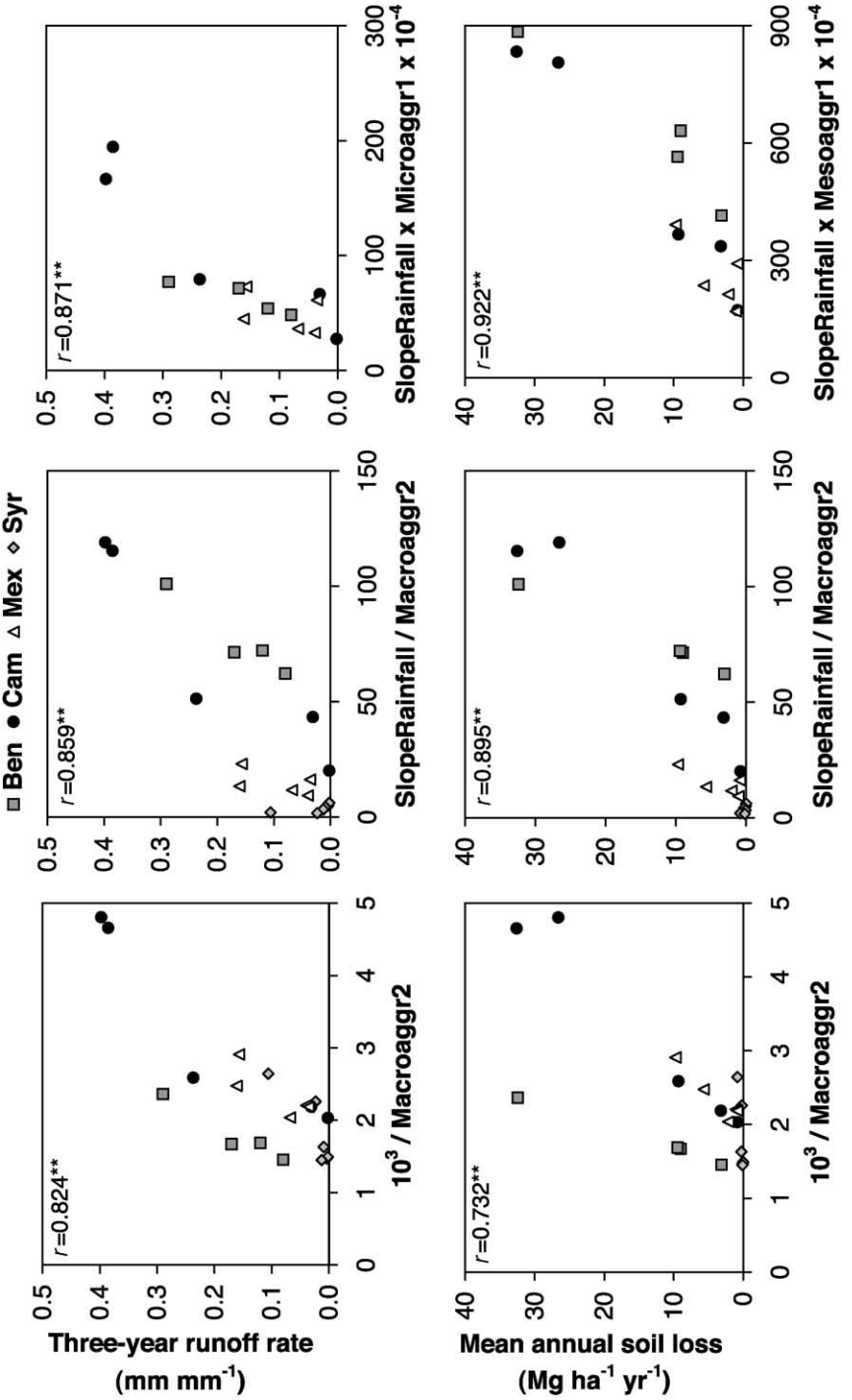
$$\text{erosion index} = a_1 + a_2 + a_3 + a_4 + 2b + 3c + 4d. \quad (1)$$

This erosion index was averaged over the three transects of each functional segment. Erosion features were not visible on some 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.

2.4. Soil analysis

Water stability of aggregates was determined on 2-mm sieved, air-dried soil samples of 4 g, in four replicates, using a test adapted from Kemper and Rosenau (1986). Each sample was rapidly immersed in deionized water for 30 min (Aveyron) or 2 h (runoff plots and Aude); both immersion times were assumed to give equivalent results. The sample was then wet-sieved using a motor-driven holder lowering and raising 0.2-mm sieves in containers of water, following Kemper and Rosenau (1986); the stroke length was 1.3 cm

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


Ben Cam Mex Syr
r=0.824**
r=0.859**
r=0.871**
r=0.732**
r=0.895**
r=0.922**
Three-year runoff rate (mm mm-1)
Mean annual soil loss (Mg ha-1 yr-1)
10³ / Macroaggr2
SlopeRainfall / Macroaggr2
SlopeRainfall x Microaggr1 x 10-4
SlopeRainfall x Mesoaggr1 x 10-4

and the sieving frequency was 35 cycles min^{-1} for 6 min. The fraction <0.2 mm was collected to determine fraction <0.02 mm by sedimentation (pipette method); this fraction <0.02 mm was denoted microaggregate fraction (Microaggr1). The fraction >0.2 mm was dried at 105 °C and weighed; next it was sieved into dispersive NaOH solution (0.05 M) for 30 min using the same device, then dried at 105 °C and weighed to determine coarse sand content (with coarse organic matter weight being considered as negligible). Macroaggregate (>0.2 mm) and mesoaggregate (0.02–0.2 mm) fractions (Macroaggr1 and Mesoaggr1) were defined as follows:

$$\text{Macroaggr1} = \text{Fraction} > 0.2 - \text{Coarse sands} \quad (2)$$

$$\text{Mesoaggr1} = 1000 - \text{Coarse sands} - \text{Macroaggr1} - \text{Microaggr1}. \quad (3)$$

Coarse sand, Fraction >0.2, Macroaggr1, Mesoaggr1 and Microaggr1 were expressed in g kg^{-1} soil <2 mm. Following Kemper and Rosenau (1986), macro-, meso- and microaggregate fractions were also determined on a basis free of coarse sand (Macroaggr2, Mesoaggr2 and Microaggr2, respectively), as follows:

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

$$\text{Mesoaggr2} = 1000\ \text{Mesoaggr1}/(1000 - \text{Coarse sands}) \quad (5)$$

$$\text{Microaggr2} = 1000\ \text{Microaggr1}/(1000 - \text{Coarse sands}), \quad (6)$$

with Macroaggr2 + Mesoaggr2 + Microaggr2 = 1000 g kg^{-1} soil <0.2 mm. The macroaggregate fraction (>0.2 mm) included aggregates only, whereas meso- and microaggregate fractions (0.02–0.2 and <0.02 mm, respectively) included genuine aggregates as well as elementary particles of the corresponding sizes.

As regards the experiment carried out in Syria (Shinjo et al., 2000), determination of topsoil aggregate stability differed from ours in the following ways: soil samples were collected from the surface horizons, whose depth ranged from 3 to 11 cm (instead of 0–10 cm), and only 1–2 mm dry aggregates were tested (instead of <2 mm dry soil); wet-sieving followed immediately after immersion (instead of after a delay of 30 min or 2 h), stroke length was 5 cm and sieving frequency 30 cycles min^{-1} for 5 min (instead of 1.3 cm and 35 cycles min^{-1} for 6 min, respectively); only macroaggregate content was determined (>0.25 mm, instead of >0.20 mm).

Total carbon content of samples from Aveyron, Benin, Cameroon and Mexico was determined by dry combustion using an Elemental Analyser (CHN 600, Leco, St. Joseph, MI).

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 h)$^{-1}$, respectively).

Table 2
Semi-quantitative assessment of the frequency of erosion features and topsoil (0–10 cm) content in stable macroaggregates (> 0.2 mm), on hillsides of southern France

Hillside/segment	Assessment of erosion features																				Aggregation	
	Replicate 1							Replicate 2							Replicate 3							Erosion index	Macroaggr1	Macroaggr2
	a_1	a_2	a_3	a_4	b	c	d	a_1	a_2	a_3	a_4	b	c	d	a_1	a_2	a_3	a_4	b	c	d			
Couteille 1/*a*	Recently tilled																						178	255
Couteille 1/*b*	Recently tilled																						154	245
Couteille 1/*c*	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	2	301	441
Couteille 2/*a*	Recently tilled																						178	255
Couteille 2/*b*[a]	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	4	122	166
Couteille 2/*c*[a]	1	2	0	0	0	0	0	2	0	0	0	0	0	0	2	0.5	0	0	0	0	0	2.5	148	255
Pradals 1/*a*	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	6	136	203
Pradals 1/*b*[a]	0	0	0	0	2	0	0	0	0	0	0	0.5	1	0	0	0	0	0	2	0	0	4	96	124
Pradals 1/*c*	Recently tilled																						91	133
Pradals 1/*d*[a]	1	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	2	185	272
Pradals 1/*e*	Recently tilled																						185	272
Pradals 2/*a*	0	1	1	0	2	1	0	0	2	0	0	1	0	0	0	0	1	1	0	2	0	7	69	123
Pradals 2/*b*	0	1	1	1	2	1	0	0	0	0	0	1.5	1	0	1	0	1	1	1	0	0	7	69	123
Pradals 2/*c*	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	4	237	367
Ginestas 1/*a*	1	1	0	0	2	0	0	0	0	0	0	3	0	0	0	0	0	0	3	0	0	6	216	235
Ginestas 1/*b*	1	1	0	0	1	2	0	0	0	0	0	0	2	0	0	0	0	0	1	1	0	7	51	55
Ginestas 2/*a*[a]	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	2	84	89
Pech–Cerda/*a*[a]	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	2	540	562
Pech–Cerda/*b*	Not measured																						402	425
Pech–Cerda/*c*	1	2	1	0	0	2	0	1	0	0	0	3	0	0	0	1	1	0	1	0	0	7	95	104
Pech–Cerda/*d*	1	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	474	489
Roquentin/*a*	1	1	1	0	0	0	0	1	0	0	1	0	0	0	2	1	1	1	1	1	0	5	238	345
Roquentin/*b*	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	1	0	0	2	226	339

a_1, a_2, a_3 and a_4 were the frequencies of sedimentation crusts, stones on the soil surface, small pedestals and microcliffs, respectively, whereas b, c and d were the frequencies of grooves, rills and gullies, respectively; the erosion index was defined as the sum $a_1+a_2+a_3+a_4+2b+3c+4d$.
Macroaggr1 in g kg^{-1} soil <2 mm and Macroaggr2 in g kg^{-1} soil <0.2 mm.
[a] Functional segment with conservation practices.

2.5. Statistical analysis

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

3. Results

3.1. Rainfall simulation on microplots in Aveyron, southern France

Within the population formed by the seven plots, runoff and erosion measured under simulated rainfall on microplots were correlated with topsoil (0–10 cm) aggregate stability or carbon content C (Fig. 1). In this manner, runoff depth and soil loss during the initial 30 min of rainfall were significantly correlated with Macroaggr1 ($r = -0.937$** and $r = -0.811$*, respectively) and with Macroaggr2 ($r = -0.950$** and $r = -0.900$**, respectively), but not with C ($r \geq -0.753^{NS}$). During runoff steady state, which was reached 50 to 90 min after the onset of rainfall, 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 ($r = -0.773$*). Other correlations between rainfall simulation parameters and aggregation were not significant, except that between the 30-min runoff depth and Mesoaggr2 ($r = 0.808$*). Runoff and erosion were thus closely linked with topsoil macroaggregate stability during the first part of the rainfall. During the second part of the rainfall, they were mainly linked with C, and to a lesser extent with macroaggregate stability; however, rainfall with an intensity of 60 mm h^{-1} and lasting 30 min occurs only every 10 years in this region.

3.2. Runoff plots in Benin, Cameroon, Mexico and Syria

Correlation coefficients involving Macroaggr1 and Macroaggr2 were calculated within the population formed by all 20 runoff plots, including those in Syria. Correlations involving other aggregation parameters or C were only determined within the population formed by the 14 plots in Benin, Cameroon and Mexico.

There were simple linear correlations between runoff or erosion measured on runoff plots and topsoil aggregation parameters (Fig. 2). In this manner, the 3-year runoff rate and mean annual soil loss 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 ($|r| < 0.5^{NS}$).

Multiple linear correlations between (i) 3-year runoff rate or mean annual soil loss and (ii) slope gradient, mean rainfall erosion index and aggregation parameters were closer than correlations involving only aggregation parameters. With this approach, the 3-year runoff rate was significantly correlated with slope gradient, mean rainfall erosion index and Macroaggr2, 1/Macroaggr1, 1/Macroaggr2, Mesoaggr1, Mesoaggr2, Microaggr1 or Microaggr2 ($0.84^{**} < |r| < 0.92^{**}$). Similarly, the mean annual soil loss was correlated

with slope gradient, mean rainfall erosion index and Macroaggr2, 1/Macroaggr1, 1/Macroaggr2, Mesoaggr1 or Mesoaggr2 ($0.82^{**} < |r| < 0.94^{**}$).

There were also simple linear correlations between runoff rate or erosion and the product of one of the aggregation parameters (or C) multiplied by a SlopeRainfall factor; this factor was defined as the product of slope gradient (%) by mean rainfall erosion index (MJ mm (ha h)$^{-1}$). With this approach, the 3-year runoff rate and mean annual soil loss were significantly correlated with the product of SlopeRainfall factor by 1/Macroaggr2, Mesoaggr1, Microaggr1, Microaggr2 or 1/C ($0.81^{**} < r < 0.93^{**}$).

Mean annual runoff and erosion measured on runoff plots were thus closely linked with the stability of the topsoil aggregates, especially that of the macroaggregates. Correlations were improved when slope gradient and rainfall aggressiveness were taken into consideration in addition to aggregate stability.

3.3. Semi-quantitative assessment of erosion features on hillsides in Aude, southern France

Carbon content and meso- and microaggregate fractions were not determined on the samples collected for this study. Within the population formed by the 17 functional segments where the frequency of erosion features was assessed, there were significant simple linear correlations between the semi-quantitative erosion index and Macroaggr1 ($r = -0.584^{*}$) or Macroaggr2 ($r = -0.634^{**}$) (Table 2 and Fig. 3).

Conservation practices such as grass strips, ditches and vineyard planting perpendicular to the slope were observed on six segments; as such practices could reduce runoff and erosion, erosion features on those segments were assumed to be less directly related to soil aggregation. Indeed, the correlation between the erosion index and Macroaggr1 or Macroaggr2 was closer within the 11 remaining segments with no conservation practices

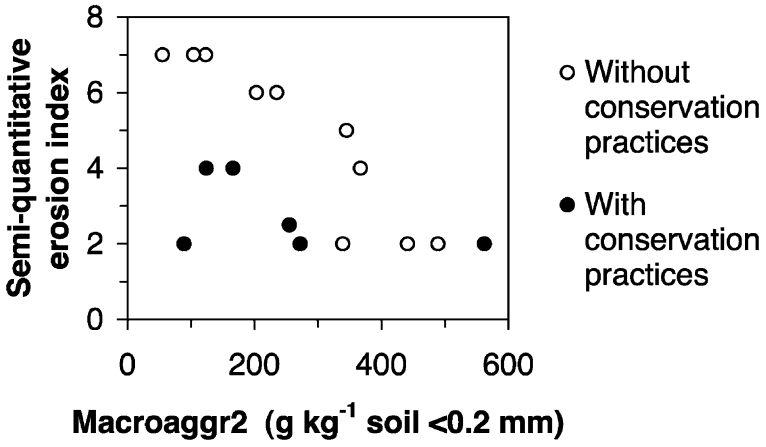


Fig. 3. Relationship between the semi-quantitative erosion index and topsoil (0–10 cm) content in stable macroaggregates (the erosion index is the sum of the weighted frequencies of erosion features observed on the hillsides; Macroaggr2 > 0.2 mm, in g kg^{-1} soil < 0.2 mm).

($r = -0.855$** and $r = -0.924$**, respectively), than within the population formed by the 17 segments.

4. Discussion

Many authors have reported negative relationships between aggregate stability and soil susceptibility to runoff and erosion (Bryan, 1968; Luk, 1977; Reichert and Norton, 1994; Amezketa et al., 1996; Le Bissonnais and 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, under simulated rainfall on microplots (Roth et al., 1987; Valentin and Janeau, 1989; Bajracharya et al., 1992; Van Dijk et al., 1996) or under natural rainfall on runoff plots (Quantin and Combeau, 1962); but each study referred to only a limited number of soil types. Our results confirmed that topsoil 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: quantification on 1-m^2 microplots under simulated rainfall in southern France; quantification on 100- to 800-m^2 runoff plots under natural rainfall in Benin, Cameroon and Mexico (with additional data on Syria from the literature); semi-quantitative determination of the frequency of erosion features on hillsides in southern France.

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 and Le Bissonnais, 1998), as was the case in our studies. As other mechanisms than slaking may determine aggregate breakdown, some authors have proposed improvements in the measurement of aggregate stability. In order to distinguish between the elementary mechanisms responsible for aggregate breakdown, i.e. slaking, microcracking through differential swelling, mechanical breakdown by raindrop impact, and physico-chemical dispersion, Le Bissonnais (1996) designed a method combining three treatments: fast wetting in water, slow wetting in water, and stirring after pre-wetting. Though rather time-consuming, this improved method also has the advantage of separating disintegration and the measurement of this disintegration, which is achieved through gentle wet-sieving in ethanol. Le Bissonnais (1996) nevertheless considered fast wetting, i.e. immersion wetting, as the simplest way to check aggregate stability, and as a good way to compare the behaviour of large ranges of soils on fast wetting under dry conditions. Moreover, using the procedure proposed by Le Bissonnais on a range of California soils, Amezketa et al. (1996) found that among the aggregate stability parameters they tested, those which involved slaking were the most closely correlated with erosion parameters under simulated rainfall. Furthermore, Loch and Foley (1994), studying a wide range of Australian soils, recommended the wetting of soil samples using simulated rainfall, because it produced results more relevant to soil behaviour under field conditions than did tests based on immersion wetting. However, they noted that immersion wetting caused similar aggregate

breakdown on average to that from rainfall wetting, and produced results significantly correlated with those from infiltration experiments under field conditions (especially when deleting the swelling soils from the data set). In addition, they suggested that, for most soils, the wetting rate was of greater importance than drop impact as a factor in aggregate breakdown on wetting. Morin and Van Winkel (1996) also questioned the importance of raindrop impact in soil crusting, as they observed the formation of a dense crust on sand protected from rain impact but located downslope from rainfall wetted clay. Moreover, Van Dijk et al. (1996), in field rainfall simulations on a silty loess, showed that runoff was better correlated with the degree of surface slaking, assessed by visual comparisons, than with the kinetic energy of rainfall or aggregate stability determined through a drop test; on the opposite, drop test and measurement of rainfall energy allowed a better prediction of splash erosion than did the assessment of slaking. Studying crust formation on a sandy clay loam Alfisol, Bajracharya and Lal (1998) reported that mechanical breakdown of aggregates by raindrop impact mainly occurred during the early stage of the rain event. Also studying crust formation but on artificial aggregates from Entisols and Inceptisols, Tanaka et al. (1999) distinguished between initial heavy rainfall, which promoted slaking, and initial gentle rainfall, which promoted weakening of aggregates subsequently disintegrated by impact and residual effect of slaking. Though several mechanisms may contribute to aggregate disintegration, slaking may thus be considered as particularly important, especially (i) in tropical or Mediterranean areas, where intense rainfall is frequent (Roose, 1996), and (ii) in soils with low exchangeable sodium proportion (ESP) and swelling clay content, as was the case in our studies.

However, aggregate disintegration is not the only mechanism involved in erosion: particle detachment through shearing by raindrops and overland flow, as well as transport by rainsplash and runoff, may also contribute to soil erosion by water (Ellison, 1947; Casenave and Valentin, 1989; Agassi and Bradford, 1999). In interrill areas, detachment by sheet flow and transport by rainsplash have often been regarded as negligible, and erosion as resulting mainly from particle detachment by raindrops and sediment transport by sheet flow (Zhang et al., 1998; Agassi and Bradford, 1999). Detachment by rainfall has even been recognized as the dominant erosive force affecting erosion rate in interrill areas, where transport capacity is generally not acknowledged to be a limiting factor (Poesen, 1992; Jayawardena and Bhuiyan, 1999). Considering that aggregate resistance to slaking greatly influences soil detachment by rainfall, especially on Mediterranean and tropical soils with low ESP and swelling clay content, it may thus be concluded that it is an important determinant of interrill erosion. 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), and it is well established that surface sealing promotes overland-flow generation, and hence, 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 frequently subject to intense rainfall. Such relationships were observed in each of our three experiments, which involved either interrill erosion alone,

particularly on 1-m^2 microplots, or both interrill and rill erosion, e.g., on the hillsides in Aude which displayed grooves and rills (Table 2).

Several authors have distinguished between detachment-limiting sediment delivery, controlled by topsoil properties such as soil strength and aggregate stability, and transport-limiting sediment delivery, controlled by the size and density of pre-detached particles (Huang, 1998; Agassi and Bradford, 1999). Based on the links between aggregate stability and erosion, we may assume that detachment-limiting conditions generally prevailed in our experimental plots. Runoff occurs when more rain falls than is absorbed by the soil, and in addition to limited infiltration capacity promoted by aggregate disintegration and subsequent surface clogging, the limited capacity of soil moisture storage has been recognized as a possible cause of erosion (Van Dijk and Kwaad, 1996; Martínez-Mena et al., 1998). However, again considering the link between topsoil aggregate stability and susceptibility to runoff and erosion, it is likely that our experiments involved infiltration excess rather than saturation excess overland flow.

Some authors have proposed to study aggregate stability using calibrated dry aggregates, e.g. 3–5 mm, instead of soil fraction <2 mm, which may contain small particles or aggregates resulting from excessive and non-controlled disintegration by initial dry-sieving (Le Bissonnais and Le Souder, 1995). However, small particles and aggregates may also result directly from soil structural conditions at sampling time (e.g., due to excessive pulverisation by disc-harrowing) and as such easily transportable particles greatly influence seal formation, discarding them and using calibrated aggregates might sometimes be inappropriate when studying soil erodibility. Moreover, it is difficult to recover large aggregates from some coarse-textured soils, which pass entirely through a 2-mm sieve during dry-sieving (e.g., our samples from Benin and Cameroon). Thus, we would have encountered some difficulty in aggregation studies using calibrated aggregates, whereas using <2-mm soil samples led to results which were closely related to field measurements and observations.

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 and Smith, 1978); for erosion modelling purposes, it might thus be suitable to express soil erodibility through topsoil aggregate stability.

5. Conclusion

Soil susceptibility to runoff and erosion was investigated in the field at several scales, from 1-m^2 microplot to hillside, and using different methods: measurements of runoff rates and soil loss under natural or simulated rainfall, semi-quantitative determination of the frequency of erosion features. The investigations were carried out in different soil and climate conditions: southern France, southern Benin, northern Cameroon, central Mexico; however all the soils had low exchangeable sodium proportion and swelling clay content, and were frequently subject to intense rainfall. Soil susceptibility to runoff and erosion was

closely related to the stability of topsoil (0–10 cm) aggregates, assessed through immersion of 2-mm sieved, air-dried samples (which actually checks aggregate resistance to slaking). This relationship was improved when variables such as climate aggressiveness, slope and the existence of conservation practices were considered in addition to aggregate stability.

Thus, simple laboratory determination could provide data significantly correlated with those resulting from more expensive or time-consuming field investigations. The resistance of 2-mm sieved, air-dried topsoil samples to slaking may thus be regarded as a relevant indicator of soil resistance to runoff and erosion at scales varying from m^2 to ha, especially on low-ESP non-swelling Mediterranean and tropical soils. The relevance of aggregate stability as an indicator of soil susceptibility to erosion has already been reported, but rarely through field investigations on a wide range of soil types, as was the case in our studies.

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