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# Field-scale run-off and erosion in relation to topsoil aggregate stability in three tropical regions (Benin, Cameroon, Mexico)

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## Summary

The influence of aggregate stability on run-off and erosion has often been reported from experiments on microplots (about 1 m$^2$) under simulated rain. Our objective was to compare the aggregate stability of topsoil (0–10 cm) with run-off and erosion from experiments on run-off plots (about 100–1000 m$^2$) under natural rain. Run-off and soil losses were measured over three years on 14 plots in Benin, Cameroon and Mexico. All plots were under herbaceous vegetation and had moderate slope length and slope declivity, but differed in climate (400–1600 mm annual rainfall), soil type (sandy clay loam Nitosol, loamy sand Ferralsol, loamy Regosol), and management (from savanna to long-duration mouldboard ploughing). The stability of aggregates was determined by immersing and wet-sieving 2-mm sieved air-dried samples into water.

Mean annual run-off rate and soil losses generally increased, and the proportion of stable macroaggregates (> 0.2 mm) decreased, with increasing duration and intensity of tillage, and with decreasing cover on the soil surface. For all 14 plots, run-off and soil losses were closely correlated with aggregate stability; correlations were improved when slope gradient and climate aggressivity were considered in addition to aggregation. Slaking, the main mechanism of aggregate breakdown which occurs when dry soil is immersed, accounted well for run-off and erosion. The stability of topsoil aggregates seems therefore to be a valuable indicator of field-assessed run-off and erosion for plots on moderate slopes with herbaceous vegetation.

**Relation entre les ruissellements et pertes en terre mesurés en parcelles d'érosion et la stabilité des agrégats de l'horizon de surface dans trois régions intertropicales (Bénin, Cameroun, Mexique)**

## Résumé

Des relations entre agrégation, ruissellement et érosion sont souvent établies sur microparcelles (environ 1 m$^2$), sous pluies simulées. Notre objectif était d'étudier ces relations en parcelles d'érosion (100 à 1000 m$^2$), sous pluies naturelles. Ruissellement et érosion ont été mesurés pendant trois ans sur 14 parcelles au Bénin, au Cameroun et au Mexique. Toutes avaient une pente de longueur et de déclivité modérées et étaient sous végétation herbacée, mais elles différaient par le climat (pluviosité de 400 à 1600 mm an$^{-1}$), le type de sol (sol ferrallitique sablo-argileux, sol ferrugineux tropical sableux, régosol limono-sablo-argileux) et le mode de gestion (de la savane à la culture continue mécanisée). La stabilité des agrégats de l'horizon 0–10 cm a été déterminée par immersion puis tamisage dans l'eau d'échantillons préalablement séchés à l'air et tamisés à 2 mm.

Dans l'ensemble, le ruissellement et l'érosion annuels moyens augmentaient, et le taux de macroagrégats (> 0.2 mm) stables diminuait, avec l'ancienneté du défrichement, l'intensité du travail du sol et la dénudation du sol. Sur l'ensemble des parcelles, ruissellement et érosion annuels moyens étaient étroitement corrélés avec la stabilité des agrégats; les corrélations étaient améliorées en



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considérant la pente et le climat en plus de l'agrégation. L'éclatement, principal mécanisme de désagrégation lors de l'immersion de sol sec dans l'eau, rendait donc compte de l'érodibilité au champ. La stabilité des agrégats de l'horizon de surface semble ainsi un indicateur pertinent du ruissellement et de l'érosion à l'échelle de la parcelle et de l'année, pour des situations sous végétation herbacée avec une pente modérée.

## Introduction

Soil erosion by water involves detachment and transport of particles by raindrops and by run-off, followed by deposition. The main mechanisms of detachment are the disintegration of aggregates by slaking, cracking, dispersion, and shearing by raindrop impact or run-off. Slaking results from compression of air entrapped inside rapidly wetted aggregates (Yoder, 1936; Hénin *et al.*, 1958); cracking results from differential swelling and shrinkage; dispersion results from the reduced cohesion between wetted colloidal particles (Le Bissonnais, 1996); shearing, as well as transport by splash and run-off, depend largely on kinetic energy of raindrops and run-off, but also on the properties of the soil itself (Casenave & Valentin, 1989). As run-off increases according to the length of the slope, its shearing and transport capacities also increase, and erosion evolves from sheet erosion to more severe rill erosion (Roose, 1996).

The depth of run-off and loss of soil during a rainfall event or sequence of events may be assessed on different scales: catchment ($> 10^4\,m^2$), plot ($10–10^4\,m^2$), or microplot ($< 10\,m^2$) (Mutchler *et al.*, 1988; Hudson, 1993). Catchments are generally heterogeneous in terms of soil and vegetation, and thus measurements at catchment outlets provide balances resulting from contributions of spatial subunits with different erosional responses, which are difficult to distinguish (Le Bissonnais *et al.*, 1998). Measurements at the microplot scale underestimate soil losses because run-off flow cannot gain velocity and concentrate on a short slope (Le Bissonnais *et al.*, 1998). Moreover, edge effects are important on such microplots (Mutchler *et al.*, 1988). At the intermediate plot scale, slope length is sufficient for run-off to concentrate, and sedimentation can be avoided as long as the gradient is even. These plots may easily be set up in homogeneous edaphic and vegetal conditions. They receive natural rain and can provide results on an event or yearly basis. It is therefore not surprising that they have received much attention (Mutchler *et al.*, 1988; Roose & Sarrailh, 1989; Hudson, 1993).

Soil susceptibility to run-off and erosion, or soil erodibility, may also be evaluated by laboratory tests, easy to implement and carried out on small ($< 100\,g$) soil samples (Bryan, 1968). The relevance of such tests, which involve few elementary mechanisms, is generally assessed through comparisons with run-off and soil loss under simulated rain. Several references have reported significant negative correlations between (i) topsoil aggregate stability of rapidly wetted samples and (ii) run-off or soil loss measurements under simulated rain during laboratory experiments (Bryan, 1968; Reichert & Norton, 1994; Le Bissonnais & Arrouays, 1997) or field experiments on microplots (Roth *et al.*, 1987; Barthès *et al.*, 1999). Such correlations demonstrated the relevance of topsoil aggregate stability as an erodibility indicator for soil samples or microplots under simulated rain; but considering the behaviour of soil samples or microplots as a reference for erosion studies is questionable.

Our objective was to assess the relations between (i) annual run-off and erosion on 100- to 800-$m^2$ run-off plots under natural rain and (ii) aggregate stability of immersed dry topsoil samples. Three experimental sites were studied, one in Benin on a sandy clay loam, another in Cameroon on a loamy sand, and the third in Mexico on a loamy soil. All the run-off plots had a slope length $< 50\,m$ and a slope gradient $< 5\%$, and were under annual crop or savanna.

## Materials and methods

### *Run-off plots of Agonkanmey (Benin)*

Agonkanmey (6°24′N, 2°20′E) is near Cotonou, in southern Benin. The climate is subhumid-tropical, with two rainy seasons, from March to July and from September to November. Mean annual rainfall is about 1200 mm, and mean monthly rainfall is at its maximum in June (270 mm); mean annual temperature is 27°C. The landscape is dominated by low plateaux, with a relief of about 20 m. The soils are Dystric Nitosols (FAO) or Typic Tropudults (USDA), and have a sandy loam surface layer overlying sandy clay loam at a depth of about 50 cm. Most of the land is cultivated, mainly for maize, beans, cassava, peanuts, often associated with oil palm.

The study was carried out on four 30-m long by 8-m wide experimental plots with 4% slope. Each was surrounded by half-buried sheets and fitted out with a collector draining run-off and sediments towards two tanks in series. When the first tank was full, additional flow moved through a divisor towards a second tank, both having a 2–3 $m^3$ collection capacity. The current experiment began in 1988, but the run-off and erosion data collected for our study related to years 1995–97. Four cultivation treatments were tested, one per plot: (i) traditional pure maize cropping system, without any input; (ii) pure maize cropping system with mineral fertilizers; (iii) intercropping of maize and a legume cover crop every year, with no fertilizer input; (iv) same as the previous treatment, with intercropping of maize and legume one year out of two, and pure maize cultivation during the second year. Maize was always cropped during the first rainy season, with manual superficial hoe cultivation. The legume cover crop, mucuna (*Mucuna pruriens* var. *utilis*), was sown one month after maize sowing, and completed its growth once maize had been harvested. Further information on the site and soil has been given by Azontonde (1993) and Azontonde *et al.* (1998).

Annual rainfall was 1000, 1126 and 1558 mm in 1995, 1996 and 1997, respectively. Following Wischmeier & Smith (1978), the rainfall erosion index was determined by adding, over a year, the products of the energy of each rainstorm multiplied by its maximum 30-min intensity. In order to allow comparisons with data from the literature, we expressed this index in American units, i.e. hundreds of foot-tons per acre times inches per hour (which may be converted into MJ mm $(\mathrm{ha\,h})^{-1}$ when multiplied by 17.35). At Agonkanmey, this index reached 505, 563 and 779 American units in 1995, 1996 and 1997, respectively, i.e. an average of 616 (Azontonde, unpublished data).

### *Run-off plots of Mbissiri (Cameroon)*

Mbissiri (8°23′N, 14°33′E) is near Tchollíré, 250 km away from Garoua, in northern Cameroon. The climate is subhumid-tropical, with one rainy season from April to October. Mean annual rainfall is about 1300 mm, and mean monthly rainfall is at its maximum in August (350 mm); mean annual temperature is 26°C. The experimental plots were located on a long slope with gradient <3%, at 370 m elevation, below a residual hill with ironstone. The soils are sandy Orthic Ferralsols (FAO) or sandy Plinthic Haplorthox (USDA). The natural vegetation is a shrub and arboreal savanna. The main crops are cotton and food crops (sorghum, maize, cassava, peanuts, beans).

Five 20-m long by 5-m wide run-off plots had been established in 1991, and instrumented as in Agonkanmey, with an additional sedimentation tank. Run-off and soil losses data were collected from 1991 to 1994, but our study related to years 1992–94. Plots were cropped in maize (1991 and 1993) and cotton (1992 and 1994). Among the five plots, two were on a 30-year-old clearing with a 2.5% slope, and involved mechanized mouldboard ploughing, weeding and mounding with the rows parallel to the slope, and mineral fertilizers; plant residues were removed on one plot, but were spread prior to tillage on the other one. Two other plots were on a 1991 clearing with a 2% slope; one involved the same cultivation practices as the previous plots, residues being removed, whereas the other treatment was direct drilling with mineral fertilizers and mechanized mounding with the rows parallel to the slope. The fifth plot was a savanna (30-year-old fallow) with a 1% slope and 10 m in width. Further information on the site and soil has been given by Boli *et al.* (1993) and Boli (1996).

Annual rainfall was 1511, 1072 and 1353 mm in 1992, 1993 and 1994, respectively. The rainfall erosion index (Wischmeier & Smith, 1978) reached 785, 496 and 433 American units in 1992, 1993 and 1994, respectively, i.e. an average of 571 (Boli, 1996).

### *Run-off plots of San Miguel Tlaixpan (Mexico)*

San Miguel Tlaixpan (19°30′N, 98°48′W) is near Texcoco, in the Mexico valley, at the piedmont of the Sierra Nevada. The climate is subhumid-temperate, with a rainy season from April to October, then a marked dry season. Mean annual rainfall is about 700 mm, and mean monthly rainfall is at its maximum in August (150 mm); mean annual temperature is 13°C. The experimental plots were located at 2600 m elevation and had a 10% natural slope. The soils are loamy Eutric Regosols (FAO) or Lithic Ustorthents (USDA); they are from volcanic origin (tuff) and result from splitting up and loosening of an outcropping indurated horizon with fragipan properties, called tepetate (Quantin *et al.*, 1999). Natural vegetation is oak, pine and fir forest. The main crops are maize, beans, wheat, barley, oats and lucerne.

Run-off plots, about 40 m long by 20 m wide, were established in 1993, and instrumented as in Agonkanmey. Run-off and soil losses data were collected from 1993 to 1996, but our study related to years 1993–95 (modifications in the experimental design occurred in 1996). Cultivation of the tepetate involved deep subsoiling by bulldozer, terracing, mechanized mouldboard ploughing then disc-harrowing. Among the five plots studied, the reference plot was subsoiled to 40 cm, double disc-harrowed, then annually fertilized with moderate amounts of N, P and K; it was under mixed cropping in barley–vetch, maize–string bean–bean, and maize–string bean, in 1993, 1994 and 1995, respectively, with plant residues lying on the ground after harvesting; this reference plot had a 4.4% slope. The second plot differed from the reference plot in that it was fourfold disc-harrowed (instead of twofold) and had a 2.5% slope. The third plot differed from the reference plot in monocropping of barley (1993) and maize (1994, 1995), instead of mixed cropping, and in a 3.2% slope. The fourth plot differed from the reference plot in manure application, no mineral fertilization, and a 3.4% slope. The fifth plot differed from the reference plot in subsoiling to 60 cm (instead of 40 cm), 13 m width (instead of about 20 m) and a 4.7% slope. Further information on the site and soil has been given by Quantin (1997) and Prat *et al.* (1997).

Annual rainfall was 411, 736 and 768 mm in 1993, 1994 and 1995, respectively. The rainfall erosion index (Wischmeier & Smith, 1978) reached 55, 124 and 113 American units, respectively, i.e. an average of 97 (Prat *et al.*, 1997).

### *Run-off and soil losses measurements*

Run-off amount was assessed on every plot after each rainfall event or sequence of events, by measuring the volume of water in each tank and multiplying it by a coefficient depending on divisors. This run-off amount was referred to plot area, in order to calculate run-off depth (mm). Annual run-off rate (mm $mm^{-1}$) was defined as the ratio of annual run-off depth to annual precipitation; three-year run-off rate (mm $mm^{-1}$) was defined as the ratio of run-off depth to precipitation over three years.

Wet coarse sediments were collected at the bottom of the first tank and weighed. At Agonkanmey, dry coarse sediment amount was deduced from oven-drying of aliquots; at Mbissiri, it was deduced from calibration curves, drawn up by weighing increasing amounts of dry topsoil in a bucket filled up with water; at San Miguel, the whole coarse sediments were oven-dried then weighed. Suspended sediment amount was assessed by flocculation and oven-drying of aliquots collected in the second tank (Mbissiri) or in every tank (Agonkanmey, San Miguel). These different determinations of dry-coarse and -suspended sediment amounts were supposed to give equivalent results. Annual soil losses (t $ha^{-1}$ $year^{-1}$) were defined as the sum of dry-coarse and -suspended sediment amounts over one year; mean annual soil losses over three years (t $ha^{-1}$ $year^{-1}$) were also calculated.

### *Soil sampling and analyses*

Composite soil samples were collected on each plot at a 0–10 cm depth, each sample being constituted by three (Agonkanmey) or about 10 (Mbissiri, San Miguel) individual samples. Soils were sampled at the beginning of 1998, 1995 and 1997 in Agonkanmey, Mbissiri and San Miguel, respectively, then air-dried and sieved using a 2-mm sieve.

Water-stability of aggregates was determined using a test inspired by Kemper & Rosenau (1986). Four grams of 2-mm sieved air-dried soil were rapidly immersed into deionized water for 2 h, then wet-sieved through a 0.2-mm sieve with an adapted device (this device consisted of a motor-driven holder lowering and raising sieves in containers of water, following Kemper & Rosenau, 1986). On the one hand, the fraction < 0.2 mm was collected to determine fraction < 0.02 mm by sedimentation (pipette method); this fraction < 0.02 mm was called the microaggregate fraction (Microaggregate 1). On the other hand, the fraction > 0.2 mm was oven-dried at 105°C and weighed; next it was sieved into dispersive NaOH solution (0.05 M) for 30 min with the same device, then oven-dried and weighed to determine coarse sand content, with coarse organic matter being neglected. Macroaggregate (> 0.2 mm) and mesoaggregate (0.02–0.2 mm) fractions (Macroaggregate 1 and Mesoaggregate 1) were defined as follows.

$$\text{Macroaggregate 1} = \text{Fraction} > 0.2 - \text{Coarse sand} \quad (1)$$

$$\text{Mesoaggregate 1} = 1000 - \text{Coarse sand} - \text{Macroaggregate 1} - \text{Microaggregate 1}. \quad (2)$$

Fraction > 0.2, Macroaggregate 1, Mesoaggregate 1 and Microaggregate 1 were expressed in g $kg^{-1}$ soil < 2 mm. Following Kemper & Rosenau (1986), macro-, meso- and microaggregate fractions were also determined on a basis free of coarse sand (Macroaggregate 2, Mesoaggregate 2 and Microaggregate 2, respectively) as

$$\text{Macroaggregate 2} = 1000\ \text{Macroaggregate 1}/(1000 - \text{Coarse sand}) \quad (3)$$

$$\text{Mesoaggregate 2} = 1000\ \text{Mesoaggregate 1}/(1000 - \text{Coarse sand}) \quad (4)$$

$$\text{Microaggregate 2} = 1000\ \text{Microaggregate 1}/(1000 - \text{Coarse sand}), \quad (5)$$

with Macroaggregate 2 + Mesoaggregate 2 + Microaggregate 2 = 1000 g $kg^{-1}$ soil < 0.2 mm. The macroaggregate fraction (> 0.2 mm) included aggregates only, whereas the mesoaggregate fraction (0.02–0.2 mm) included genuine aggregates, fine sand (0.05–0.2 mm) and coarse silt (0.02–0.05 mm); in the same way, the microaggregate fraction (< 0.02 mm) included small aggregates, fine silt (0.002–0.02 mm) and clay (< 0.002 mm). Measurements were made on four replicates for each soil sample.

Grain-size composition of 2 mm-sieved soil samples was determined by pipette, after destruction of the organic matter and total dispersion; five fractions were separated: clay (< 0.002 mm), fine silt (0.002–0.02 mm), coarse silt (0.02–0.05 mm), fine sand (0.05–0.2 mm) and coarse sand (0.2–2 mm). Total carbon (C) and nitrogen (N) contents were determined by dry combustion using an Elemental Analyser (CHN 600, Leco Corporation, St Joseph, MI). The pH in water was determined with a soil:solution ratio of 1:2.5.

### *Statistical analyses*

Differences in three-year run-off rate and in mean annual soil losses between plots were tested by a Student paired *t*-test. Differences in mean aggregate contents between plots were tested by a Student unpaired *t*-test. In both cases, there was no assumption on normality. As means were calculated from the same number of years (erosion) or replicates (aggregation) for every plot, there was also no assumption on variance equality (Dagnélie, 1975).

**Table 1** Grain-size composition, total carbon content (C), total nitrogen content (N) and pH in water of 0–10 cm soil samples, and slope gradient of plots

| Country and treatment | <2 μm /g 100 g$^{-1}$ | 2–50 μm /g 100 g$^{-1}$ | 50–200 μm /g 100 g$^{-1}$ | 200–2000 μm /g 100 g$^{-1}$ | C /g kg$^{-1}$ | N /g kg$^{-1}$ | pH | Slope /% |
|---|---|---|---|---|---|---|---|---|
| Benin | | | | | | | | |
| Mucuna every year | 14 | 8 | 22 | 55 | 12.3 | 1.01 | 5.0 | 4.0 |
| Mucuna one year out of two | 18 | 5 | 22 | 53 | 9.3 | 0.80 | 5.2 | 4.0 |
| No input | 22 | 8 | 19 | 50 | 6.3 | 0.57 | 5.1 | 4.0 |
| Mineral fertilizers | 13 | 4 | 21 | 60 | 7.8 | 0.67 | 5.2 | 4.0 |
| Cameroon | | | | | | | | |
| Savanna | 8 | 10 | 22 | 60 | 8.1 | 0.40 | 6.6 | 1.0 |
| Recent clearing, direct drilling | 6 | 5 | 23 | 67 | 3.9 | 0.22 | – | 2.5 |
| Recent clearing, ploughing | 7 | 10 | 21 | 63 | 3.7 | 0.19 | – | 2.5 |
| Formerly tilled, no residue | 10 | 10 | 25 | 56 | 2.8 | 0.20 | 5.9 | 2.0 |
| Formerly tilled, with residues | – | – | – | – | 2.6 | 0.17 | 6.0 | 2.0 |
| Mexico | | | | | | | | |
| Deep subsoiling | 26 | 43 | 18 | 11 | 3.3 | 0.24 | 6.9 | 4.7 |
| Monocropping | 24 | 40 | 20 | 14 | 3.0 | 0.21 | 7.4 | 3.2 |
| Manure application | 25 | 33 | 17 | 22 | 4.8 | 0.28 | 7.9 | 3.4 |
| Fourfold disc-harrowing | 30 | 36 | 19 | 12 | 2.8 | 0.16 | 7.6 | 2.5 |
| Reference | 24 | 37 | 21 | 15 | 3.7 | 0.22 | 7.4 | 4.4 |

**Table 2** Run-off rate and soil losses on a one- and three-year basis

| Country (with annual rainfall) and treatment | Annual run-off rate /mm mm$^{-1}$ | | | | Annual soil losses /t ha$^{-1}$ year$^{-1}$ | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Year 1 | Year 2 | Year 3 | Three-year basis | Year 1 | Year 2 | Year 3 | Mean | SE |
| Benin (rainfall: 1000, 1126 and 1558 mm in year 1, 2 and 3) | | | | | | | | | |
| Mucuna every year | 0.04 | 0.08 | 0.11 | 0.08 a | 1.3 | 2.5 | 5.5 | 3.1 a | 1.2 |
| Mucuna one year out of two | 0.12 | 0.16 | 0.20 | 0.17 c | 3.9 | 10.3 | 12.8 | 9.0 a | 2.7 |
| No input | 0.16 | 0.25 | 0.40 | 0.29 abc | 10.6 | 40.4 | 46.3 | 32.4 a | 11.0 |
| Mineral fertilizers | 0.08 | 0.12 | 0.15 | 0.12 b | 3.8 | 8.9 | 15.6 | 9.4 a | 3.4 |
| Cameroon (rainfall: 1511, 1072 and 1353 mm in year 1, 2 and 3) | | | | | | | | | |
| Savanna | 0.005 | 0.000 | 0.000 | 0.002 a | 2.4 | 0.1 | 0.0 | 0.8 a | 0.8 |
| Recent clearing, direct drilling | 0.072 | 0.003 | 0.005 | 0.031 a | 6.8 | 0.8 | 2.0 | 3.2 a | 1.8 |
| Recent clearing, ploughing | 0.298 | 0.199 | 0.196 | 0.237 b | 14.7 | 6.7 | 6.5 | 9.3 b | 2.7 |
| Formerly tilled, no residue | 0.416 | 0.311 | 0.405 | 0.385 c | 28.9 | 25.2 | 43.8 | 32.6 bc | 5.7 |
| Formerly tilled, with residues | 0.452 | 0.380 | 0.349 | 0.398 c | 32.8 | 20.9 | 26.0 | 26.6 c | 3.5 |
| Mexico (rainfall: 411, 736 and 768 mm in year 1, 2 and 3) | | | | | | | | | |
| Deep subsoiling | 0.094 | 0.224 | 0.124 | 0.157 a | 5.8 | 15.5 | 7.9 | 9.7 a | 2.9 |
| Monocropping | 0.056 | 0.254 | 0.124 | 0.161 ab | 1.0 | 12.0 | 4.1 | 5.7 b | 3.3 |
| Manure application | 0.033 | 0.104 | 0.050 | 0.068 b | 1.3 | 3.7 | 1.5 | 2.1 ab | 0.8 |
| Fourfold disc-harrowing | 0.021 | 0.064 | 0.026 | 0.040 ab | 0.8 | 1.4 | 1.0 | 1.1 ab | 0.2 |
| Reference | 0.023 | 0.061 | 0.007 | 0.036 b | 0.6 | 1.6 | 0.3 | 0.9 ab | 0.4 |

Within a situation and in the same column, values followed by different letters are significantly different at $P = 0.05$. SE, standard error.

## Results

Some properties of the run-off plots (0–10 cm soil layer and slope) are presented in Table 1.

### *Run-off and soil losses (Table 2)*

At Agonkanmey (Benin), Mbissiri (Cameroon) and San Miguel (Mexico), the maximum annual run-off rate reached 0.40, 0.45 and 0.25 mm mm$^{-1}$, respectively; the maximum annual soil losses reached 46, 44 and 16 t ha$^{-1}$ year$^{-1}$, respectively. At Agonkanmey, the three-year run-off rate was 1.5, 2.1 and 3.6 times greater with mineral fertilizers, biennial mucuna and no input, respectively, than with yearly mucuna; the mean annual soil losses were about 3 times greater with mineral fertilizers and biennial mucuna, and about 10 times greater with no input, than with yearly mucuna. At Mbissiri, in comparison with that measured on the directly drilled plot, the three-year run-off rate was about 8 times greater on the recently tilled plot, 12–13 times greater on the formerly tilled ones, but about one sixteenth under the savanna; the mean annual soil losses were about 3 and 8–10 times greater on the recently and formerly tilled plots, respectively, and one quarter under the savanna, than on the directly drilled plot. At San Miguel, as compared with those measured on the reference plot, the three-year run-off rate was 1.1, 1.9, 4.5 and 4.4 times greater, and the mean annual soil losses were 1.2, 2.3, 6.3 and 10.8 times greater, with fourfold disc-harrowing, manure (without mineral fertilizers), monocropping and deep subsoiling, respectively.

### *Aggregate stability (Table 3)*

The content of coarse sand in the topsoil was greater at Agonkanmey, Benin, and Mbissiri, Cameroon (450–650 g kg$^{-1}$) than at San Miguel, Mexico (100–150 g kg$^{-1}$). At Agonkanmey, Macroaggregate 2, Mesoaggregate 2 and Microaggregate 2 reached about 400–700, 300–550 and 30–50 g kg$^{-1}$ soil < 0.2 mm, respectively; at Mbissiri, they reached about 200–500, 450–650 and 70–150 g kg$^{-1}$ soil < 0.2 mm, and at San Miguel, about 350–500, 450–550 and 70–100 g kg$^{-1}$ soil < 0.2 mm, respectively. At Agonkanmey, Mbissiri and San Miguel, Microaggregate 2 was about 9–21, 1.5–7 and 3–7 times smaller than Macroaggregate 2, and about 8–12, 4–6 and 5–6 times smaller than Mesoaggregate 2, respectively.

At Agonkanmey, the macroaggregate content was 0.9 and 0.6–0.7 times greater with mineral fertilizers and no input, respectively, than with yearly mucuna; by contrast, the microaggregate content was 1.1 and 1.4–1.6 times greater. At Mbissiri, the macroaggregate content was 1.1, 0.8 and 0.5–0.7 times greater under the savanna, on the recently and formerly tilled plots, respectively, than on the untilled one, whereas the microaggregate content was 0.8, 1.2 and 1.5–2.3 greater. At San Miguel, the differences between plots were smaller, and the macro- and microaggregate contents of the reference plot generally ranged between about 0.9 and 1.1 times those of the other plots. Within each of the three situations, differences in the mesoaggregate fraction were similar to those reported for the microaggregate fraction.

### *Carbon content and relation with aggregation*

At Agonkanmey (Benin), the total carbon content C in the 0–10 cm layer ranged from 6 (no input) to 12 g kg$^{-1}$ (yearly mucuna); at Mbissiri (Cameroon) it ranged from less than 3 (on formerly tilled plots) to 8 g kg$^{-1}$ (under savanna), and at San Miguel (Mexico) from less than 3 (fourfold disc-harrowing) to 5 g kg$^{-1}$ (with manure) (Table 1).

For all 14 plots there were simple linear correlations between most of the aggregation variables of the 0–10 cm soil layer and its carbon content C (Figure 1): carbon content was significantly correlated with Microaggregate 2, Microaggregate 1, Mesoaggregate 2 and Mesoaggregate 1 ($-0.837 \leqslant r \leqslant -0.751$; $P < 0.01$), with Macroaggregate 2 ($r = 0.827$), but not with Macroaggregate 1 ($r = -0.107$). Some aggregation variables were more closely correlated with power functions of C than with linear ones: in this manner, Microaggregate 2, Microaggregate 1 and Mesoaggregate 1 were more closely correlated with $C^{-0.87}$, $C^{-1.35}$ and $C^{-0.84}$, respectively ($-0.915 \leqslant r \leqslant -0.825$; $P < 0.01$), than with C. Moreover, the fitting of these aggregation variables with power functions of C showed a threshold effect: variations of Microaggregate 2, Microaggregate 1 and Mesoaggregate 1 remained small when C was greater than 8 g kg$^{-1}$.

### *Relations between run-off or soil losses and aggregation parameters or carbon content*

For all 14 plots, there were simple linear correlations between three-year run-off rate or mean annual soil losses, and aggregation variables of the 0–10 cm soil layer, macroaggregation variables especially (Figure 2). In this manner, the three-year run-off rate and the mean annual soil losses were significantly correlated with Macroaggregate 1 and Macroaggregate 2 ($-0.686 \leqslant r \leqslant -0.617$; $P < 0.05$), with their inverse functions 1/Macroaggregate 1 and 1/Macroaggregate 2 ($0.714 \leqslant r \leqslant 0.800$; $P < 0.01$), with Mesoaggregate 2 ($r = 0.727$ and 0.689, respectively; $P < 0.01$), but not with the other aggregation variables or C ($|r| < 0.5$; $P > 0.05$).

Multiple linear correlations between (i) three-year run-off rate or mean annual soil losses, and (ii) slope gradient, mean rainfall erosion index and aggregation variables were closer than correlations involving aggregation parameters only. In this manner, the three-year run-off rate was significantly correlated with the slope gradient, the mean rainfall erosion index and Macroaggregate 2, 1/Macroaggregate 1, 1/Macroaggregate 2, or Mesoaggregate 2 ($0.913 \leqslant |r| \leqslant 0.916$; $P < 0.01$). In the same way, the mean

**Table 3** Aggregate fractions of 0–10 cm soil samples (coarse sands >0.2 mm, Macroaggregate 1 >0.2 mm, 0.02< Mesoaggregate 1 <0.2 mm, Microaggregate 1 <0.02 mm, in $g\,kg^{-1}$ soil <2 mm; Macroaggregate 2 >0.2 mm, 0.02< Mesoaggregate 2 <0.2 mm, Microaggregate 2 <0.02 mm, in $g\,kg^{-1}$ soil <0.2 mm)

| | Coarse sands | | Macro 1 | | Meso 1 | | Micro 1 | | Macro 2 | | Meso 2 | | Micro 2 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Country and treatment | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE |
| Benin | | | | | | | | | | | | | | |
| Mucuna every year | 653.6 | 5.1 | 238.0 a | 5.6 | 97.1 a | 6.0 | 11.3 a | 0.2 | 687.3 a | 15.6 | 280.0 a | 15.3 | 32.7 a | 0.7 |
| Mucuna one year out of two | 589.8 | 7.0 | 245.8 a | 7.5 | 147.6 b | 1.8 | 16.8 c | 0.2 | 598.8 b | 8.8 | 360.4 b | 8.6 | 40.9 b | 0.2 |
| No input | 612.3 | 7.0 | 163.9 c | 5.3 | 206.9 c | 11.2 | 18.0 c | 0.6 | 423.3 c | 17.0 | 532.1 c | 20.0 | 46.4 c | 0.7 |
| Mineral fertilizers | 645.2 | 10.2 | 210.0 b | 3.9 | 132.2 b | 6.3 | 12.6 b | 0.1 | 592.3 b | 6.1 | 371.9 b | 7.2 | 35.7 a | 1.2 |
| Cameroon | | | | | | | | | | | | | | |
| Savanna | 602.0 | 6.5 | 195.9 a | 6.1 | 174.3 a | 2.1 | 27.9 a | 1.1 | 491.8 a | 8.6 | 438.1 a | 6.5 | 70.1 a | 3.2 |
| Recent clearing, direct drilling | 625.5 | 3.6 | 171.1 b | 5.8 | 169.7 a | 5.7 | 33.6 b | 0.5 | 456.9 ab | 15.3 | 453.2 ab | 14.0 | 89.9 b | 1.4 |
| Recent clearing, ploughing | 633.5 | 6.9 | 141.4 c | 9.4 | 185.0 a | 10.8 | 40.1 c | 1.1 | 386.2 b | 27.0 | 504.3 b | 24.8 | 109.5 c | 2.7 |
| Formerly tilled, no residue | 471.2 | 3.0 | 113.5 cd | 8.4 | 336.7 b | 7.3 | 78.6 e | 1.0 | 214.6 c | 15.5 | 636.9 c | 14.7 | 148.6 e | 1.3 |
| Formerly tilled, with residues | 503.9 | 4.0 | 103.3 d | 11.8 | 325.5 b | 9.4 | 67.3 d | 1.0 | 208.0 c | 22.6 | 656.4 c | 21.0 | 135.6 d | 1.8 |
| Mexico | | | | | | | | | | | | | | |
| Deep subsoiling | 105.9 | 8.4 | 307.3 a | 10.1 | 494.6 a | 10.6 | 92.2 a | 1.3 | 343.7 a | 11.2 | 553.1 a | 10.0 | 103.1 a | 1.3 |
| Monocropping | 127.3 | 7.0 | 352.0 ab | 18.1 | 437.4 ab | 23.1 | 83.3 b | 2.3 | 403.9 ab | 24.0 | 500.7 ab | 22.7 | 95.4 b | 2.1 |
| Manure application | 145.1 | 8.6 | 419.2 c | 10.5 | 372.2 b | 15.8 | 63.4 c | 2.5 | 490.8 c | 16.2 | 435.0 b | 14.7 | 74.2 d | 2.4 |
| Fourfold disc-harrowing | 120.9 | 2.5 | 398.5 bc | 10.1 | 402.7 b | 10.7 | 77.9 b | 1.5 | 453.4 bc | 12.6 | 458.0 b | 11.1 | 88.6 c | 1.6 |
| Reference | 121.6 | 8.0 | 402.1 bc | 15.7 | 393.8 b | 12.0 | 82.6 b | 2.2 | 457.6 bc | 16.1 | 448.4 b | 14.4 | 94.0 bc | 2.5 |

Within a situation and in the same column, values followed by different letters are significantly different at $P = 0.05$. SE, standard error.

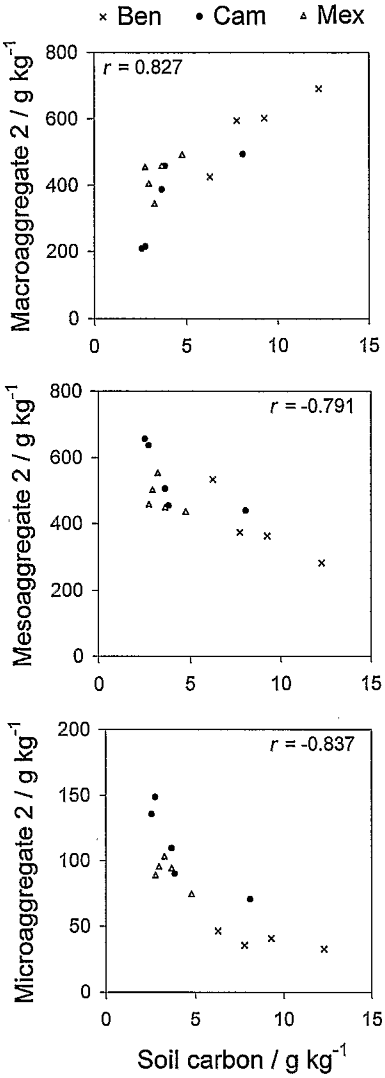


**Figure 1** Relations between water-stable aggregation and carbon content in the 0–10 cm soil layer (Macroaggregate 2 > 0.2 mm, 0.02 < Mesoaggregate 2 < 0.2 mm, Microaggregate 2 < 0.02 mm, in g kg$^{-1}$ soil < 0.2 mm).

annual soil losses were closely correlated with the slope gradient, the mean rainfall erosion index and Macroaggregate 2, Mesoaggregate 1 or Mesoaggregate 2 ($0.914 \leq |r| \leq 0.940$; $P < 0.01$).

There were also significant simple linear correlations between (i) the three-year run-off rate or mean annual soil losses and (ii) the product of one of the aggregation variables (or C) multiplied by an Environment Factor, which was defined as

$$\text{Environment Factor} = \text{Mean rainfall erosion index} \times \text{Slope gradient}. \qquad (6)$$

In this manner, the three-year run-off rate and the mean annual soil losses were significantly correlated with the product of Environment Factor by 1/Macroaggregate 2, Mesoaggregate 1, Microaggregate 1 or 1/C ($0.817 \leq r \leq 0.922$; $P < 0.01$) (Figure 3).

## Discussion and conclusion

### *Run-off and soil losses*

The plots at Agonkanmey and Mbissiri underwent similar climatic aggressiveness (as determined by rainfall erosion index), and had large sand contents. Despite different lengths, slope gradients, topsoil clay and carbon contents (all greater at Agonkanmey), they had similar maximum annual run-off rates and soil losses. The annual maxima were less at San Miguel, where the climate is less aggressive.

Within each situation, run-off and soil losses were generally greater in long-tilled plots than in recently or untilled ones (Mbissiri), and in intensely tilled plots than elsewhere (Mbissiri, San Miguel). Moreover, they were generally greater in monocropped plots than in their mixed-cropped counterparts (Agonkanmey, San Miguel). Additionally, run-off and soil losses were generally smaller on plots with mineral fertilizers than on their counterparts without fertilizers (Agonkanmey, San Miguel), probably because of better cover by vegetation. The effect of removing residues on run-off and soil losses was not clear (Mbissiri). The increase in run-off and erosion with increasing duration and intensity of tillage, and with decreasing cover, has been reported by many authors, from experiments on microplots (< 2 m$^2$) under simulated rain (West *et al.*, 1991; Bradford & Huang, 1994; Barthès *et al.*, 1998) or on run-off plots under natural rain (Roose, 1983, 1996). However, some authors indicated that increase in run-off and erosion might cease a few years after the onset of cultivation (Roose & Sarrailh, 1989); others reported that run-off might be greater from directly drilled plots than from ploughed ones (Myers & Wagger, 1996; Ghidey & Alberts, 1998).

### *Aggregate stability*

Particle-size distributions after immersion in water and wet-sieving were dominated by macro- and mesoaggregate fractions, with a small fraction of microaggregates, and hence a little dispersion in small particles. Within each situation, intensely or long-tilled plots, where run-off and erosion were large, contained smaller fractions of macroaggregates and larger ones of microaggregates than other plots (Mbissiri, San Miguel). This effect, caused by mechanical disintegration of macroaggregates and enhanced carbon mineralization by tillage, has been reported by several authors (Quantin & Combeau, 1962; West *et al.*, 1991; Barthès *et al.*, 1998). Indeed, our results stress the close relation between carbon content and aggregate stability, reported by many authors (Tisdall & Oades, 1982; Haynes *et al.*, 1991; Barthès *et al.*,

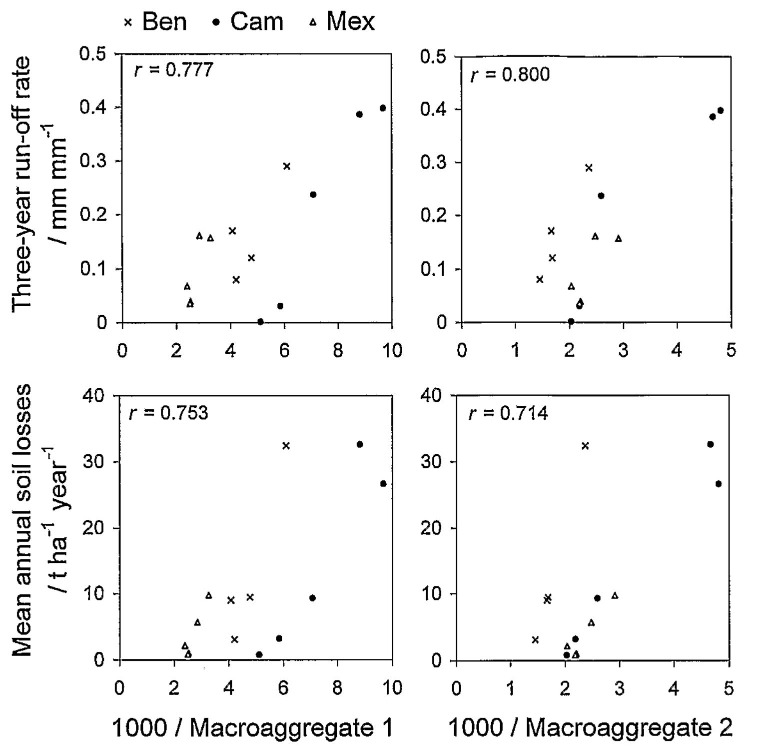


**Figure 2** Relations between three-year run-off rate or mean annual soil losses and macroaggregate (>0.2 mm) content in the 0–10 cm soil layer (Macroaggregate 1 in g kg$^{-1}$ soil <2 mm, Macroaggregate 2 in g kg$^{-1}$ soil <0.2 mm).

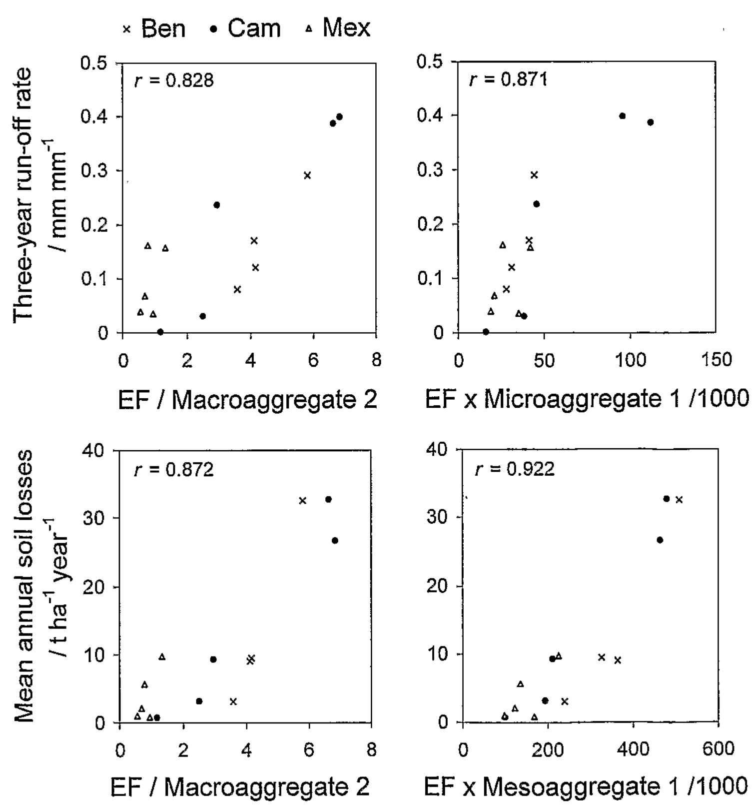


**Figure 3** Relations between three-year run-off rate or mean annual soil losses, and Environment Factor (EF= mean rainfall erosion index × slope gradient) and water-stable aggregation in the 0–10 cm soil layer (0.02< Mesoaggregate 1<0.2 mm, Microaggregate 1<0.02 mm, in g kg$^{-1}$ soil <2 mm; Macroaggregate 2>0.2 mm, in g kg$^{-1}$ soil <0.2 mm).

1998). Monocropped plots, where run-off and erosion were generally greater than in their mixed-cropped counterparts, had smaller fractions of macroaggregates and larger ones of microaggregates than the latter (Agonkanmey, San Miguel). This might be due to greater returns of residues to the soil, and consequent larger content of carbon under mixed cropping than under monocropping, as Triomphe (1996) and Azontonde *et al.* (1998) found elsewhere. There was generally less run-off and erosion from fertilized plots than from those receiving no fertilizer, but the differences in topsoil aggregation were variable: the soil receiving mineral fertilizers contained more macroaggregates and fewer microaggregates than the soil without any input (Agonkanmey), but had similar content of macroaggregates and more microaggregates than the manured soil without mineral fertilizers (San Miguel). This might also be due to the influence of cultural practices on topsoil carbon content.

### *Relations between topsoil aggregate stability and run-off or erosion*

For all 14 plots, the three-year run-off rate and mean annual soil losses were closely linked with the stability of the aggregates in the topsoil, especially that of the macroaggregates. Thus, mechanisms occurring when 2 mm-sieved air-dried topsoil samples were immersed into water, then wet-sieved, rendered a satisfactory explanation of annual run-off rate and soil losses estimated from field measurements. Slaking is the main mechanism by which aggregates disintegrate during rapid wetting of dry soil samples. Other mechanisms are involved in erosion, such as shearing and transport by raindrops or run-off. But our results did indicate that the susceptibility of aggregates to slaking matched our assessment of run-off and erosion for plots under herbaceous vegetation, having sandy to clay loam topsoil texture, and moderate slope length (< 50 m) and gradient (< 5%). Indeed, water-stable macroaggregation is known to prevent detachment of easily transportable particles, and thereby soil surface clogging and run-off (Le Bissonnais, 1996). The carbon content of the soil was a less relevant indicator of erodibility, despite the fact that there existed a close relation between carbon content and aggregate stability. Relations between aggregate stability and erodibility have been reported by many authors, from rain simulation experiments in the laboratory (Bryan, 1968; Reichert & Norton, 1994; Le Bissonnais & Arrouays, 1997) and in the field on microplots (Roth *et al.*, 1987; Barthès *et al.*, 1999). Few authors have reported such relations from field experiments under natural rain (Quantin & Combeau, 1962), as we have.

Considering slope gradient and climate aggressiveness in addition to aggregation led to better relations with run-off rate and soil losses than considering aggregate stability only. These relations then became close to those proposed by the USLE (Wischmeier & Smith, 1978) and RUSLE (Renard *et al.*, 1995) equations, with slope length (about 20–40 m), gradient (1–5%), vegetation cover (herbaceous) and support practices (none) varying within rather narrow ranges. Topsoil aggregate stability might therefore be considered as accounting for the erodibility factor, $K$, of Wischmeier & Smith (1978).

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