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COMMUN. SOIL SCI. PLANT ANAL., 30(13&14), 1929–1938 (1999)

Relationship Between Soil Erodibility and Topsoil Aggregate Stability or Carbon Content in a Cultivated Mediterranean Highland (Aveyron, France)

Bernard Barthès,[a,1] Alain Albrecht,[b] Jean Asseline,[a] Georges De Noni,[a] and Eric Roose[a]

[a]*ORSTOM-LCSC, BP 5045, 34032 Montpellier Cedex 1, France*
[b]*ORSTOM, c/o ICRAF, P.O. Box 30677, Nairobi, Kenya*

ABSTRACT

In the Rougiers de Camarès area (in the south of France), hillslopes are very susceptible to water erosion. This is the result of physical features (steep slopes, soft bedrocks, thin soils), climatic aggressiveness (frost, storms), as well as farming systems (intensive tillage, short crop cycles, land consolidation). The objective of this work was to study the relationships between soil erodibility, macroaggregate stability, and carbon content of surface samples (0-10 cm), in a Rougiers Entisol (Lithic Udorthent) under various management practices (flat or raised moldboard ploughing, superficial tillage, direct drilling, with inputs in the form of mineral fertilizers or sheep manure). The soil erodibility was assessed by field rainfall simulation (60 mm h^{-1}) on manually retilled bare dry soil; water-stable macroaggregation (>0.2 mm) was assessed by wet-sieving, after immersion in water. Runoff,

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[1] Corresponding author (e-mail address: Bernard.Barthes@mpl.orstom.fr).

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turbidity and soil losses were linked to water-stable macroaggregation and carbon content in the 0-10 cm layer. During the first 30 minutes of rainfall, runoff and soil losses were closely correlated with topsoil initial water-stable macroaggregation, but not with topsoil carbon content (although there was a correlation between water-stable macroaggregation and carbon content). At the end of the rain (runoff steady state), turbidity and soil losses were closely correlated with topsoil carbon content, and to a lesser extent, with water-stable macroaggregation. Water-stable macroaggregation (which prevents crusting) and carbon content (which has an effect upon liquidity limit, among others) were thus important determining factors of erodibility for the studied soil. The influence of management practices on soil erodibility was therefore dependent upon their effects on these factors.

INTRODUCTION

Water erosion results from detachment, mainly by rainfall, and from transport, mainly by runoff. The susceptibility of soil to erosion, or soil erodibility, is linked to soil aggregate stability, which characterizes resistance to soil breakdown: aggregate breakdown leads to detachment of particles and small aggregates, which favors superficial crusting, then runoff and transport (De Ploey and Poesen, 1985; Le Bissonnais, 1996). Moreover, soil organic matter often plays a chief part in aggregate stability (Tisdall and Oades, 1982; Oades, 1984).

In the Rougiers de Camarès area (Aveyron, in southern Massif Central), water erosion is responsible for soil degradation, particularly on cultivated hillslopes, and also leads to destruction of infrastructures. This erosion is a result of conducive physical conditions, especially numerous steep slopes, soft bedrocks and thin soils, undergoing rather aggressive climatic conditions. It is also the result of farming systems, especially intensive tillage, short crop cycles and hedge-rows destruction through land consolidation.

The aim of this work was to study the relationships between soil erodibility, assessed by field rainfall simulation, topsoil (0-10 cm) water-stable macroaggregation (>0.2 mm) and carbon content, in a Rougiers Entisol under various management practices.

MATERIALS AND METHODS

The Rougiers de Camarès area is a 1,700 km^2 wide sedimentary piedmont, with alternation of thin schist, sandstone, and claystone layers. The landscape is undulating, with altitude ranging between 300 and 600 m and gradients of up to 40%. Mean annual rainfall is ca. 800 mm and mean monthly temperature ranges between 4 and 20°C. The climate undergoes three main influences: a Mediterranean influence during the summer, with marked drought (total rainfall

<100 mm during July and August); a continental influence during the winter, with frequent frost from November to March; an oceanic influence during spring and fall, with stormy rains.

The study was carried out on 18x9 m experimental plots previously under artificial pasture, at the upper part of a hill with a slope of 5-12%. The soil was a 40-cm-deep red Entisol (Lithic Udorthent), with about 300 g kg^{-1} clay, 300 g kg^{-1} sand, and a variable gravel content (10-150 g kg^{-1}) in the top 10 cm of the soil, and containing primary components mainly (quartz, albite, muscovite, hematite). The experimental design included seven treatments: flat moldboard ploughing, raised moldboard ploughing and superficial tillage with either mineral fertilizers or sheep manure, and no tillage with sheep manure only. Flat moldboard ploughing involved complete soil inversion by ploughing with shares on 40-cm spacing, whereas raised moldboard ploughing involved half-inversion with shares on 30-cm spacing, both to a depth of 30 cm. Superficial tillage involved 10-cm-deep cultivating. In addition, all tilled treatments involved 10-cm-deep harrowing and rotavation as seedbed preparation, conventional sowing, and rolling using a cultipacker. For the no tillage treatment, planting was accomplished by means of a coulter-type planter after applying glyphosate for preplant weed control, and without seedbed preparation. Mineral fertilizers were applied at rates of 70 kg N ha^{-1}, 40 kg P ha^{-1}, and 100 kg K ha^{-1}, and sheep manure at a rate of 30 Mg ha^{-1} (with water, C, N, P, and K contents of 670 g kg^{-1}, 150 g kg^{-1}, 10 g kg^{-1}, 2 g kg^{-1}, and 15 g kg^{-1}, respectively). Soil sampling and rainfall simulations were done ten weeks after spring-oat (*Avena sativa* L.) seeding.

Rainfall simulation was carried out with an ORSTOM device (Asseline and Valentin, 1978): raindrops are produced by a nozzle mounted on a 4-m-high tower, reaching the soil surface with energy close to that of natural raindrops; rainfall is applied to a 1x1 m microplot, surrounded by a frame hammered into the soil with an opening at the lower side to collect and record surface flow. A 60 mm h^{-1} rainfall was applied to each of the experimental plots, beginning with dry soil (with a water content of 30 to 90 g kg^{-1} in the 0-5 cm layer) and going on until runoff steady state was reached. Prior to the exercise, microplot vegetation was uprooted and the top 15 cm of the soil were manually retilled. Runoff intensity (mm h^{-1}), turbidity (g L^{-1}), and solid discharge (product of runoff into turbidity, g m^{-2} h^{-1}) were measured by means of periodical runoff water sampling; values of cumulative runoff intensity and solid discharge were used to calculate runoff depth (mm) and soil loss (g m^{-2}), respectively.

Zero-10 cm undisturbed soil samples were collected close to the microplot of each experimental plot prior to rainfall, air dried, then sieved using a 2-mm sieve. Water-stability of macroaggregates (>0.2 mm) was determined by a test (Barthès et al., 1996) inspired by Kemper and Rosenau (1986): 4 g of sieved air-dried soil were rapidly immersed into deionized water for 30 minutes, then wet-sieved through a 0.2-mm sieve for 6 minutes with an adapted device. After oven drying

TABLE 1. Results of rainfall simulations, properties of the 0-10 cm soil layers (macroaggregate stability, carbon, and clay contents), and correlations between data.

		With sheep manure				With mineral fertilizers				
		Superf. tillage	Raised mold. ploug.	Flat mold. ploughing	No till	Superf. tillage	Raised mold. ploug.	Flat mold. ploughing	Correlation coeff. with Ima	with C
Runoff depth during initial 30 min	mm	0.62	1.71	1.06	1.01	0.00	1.60	2.37	-0.950**	-0.676
Steady state runoff intensity	mm h^{-1}	54.0	49.6	54.6	41.4	34.8	54.0	52.8	-0.702	-0.788*
Instantaneous turbidity after 30 min	g L^{-1}	13.8	15.7	9.0	5.5	0.0	8.0	13.7	-0.759*	-0.904**
Steady state turbidity	g L^{-1}	10.4	14.9	11.5	6.1	6.6	8.4	11.2	-0.729	-0.949**
Soil loss during initial 30 min	g m^{-2}	8.6	25.4	8.9	4.7	0.0	12.6	31.8	-0.900**	-0.753
Steady state solid discharge	g m^{-1} h^{-1}	561	739	630	253	230	452	591	-0.773*	-0.982**
Ima (stable macroaggregation index)		416	381	400	415	436	393	381	1	0.844*
C (total carbon content)	g kg^{-1}	14.9	12.8	14.0	16.9	18.2	15.5	14.2	0.844*	1
Clay content	g kg^{-1}	343	349	282	226	356	317	281	0.133	-0.086

*,**Significant at p=0.05 and p=0.01, respectively.

(at 105°C) and weighing, fraction >0.2 mm (F>0.2) was sieved into dispersive NaOH solution (0.05 *M*) for 30 minutes with the same device, then oven dried, and weighed in order to determine coarse sand weight (CS), with coarse organic matter weight being neglected. Stable macroaggregation index Ima was defined as 1,000-fold the weight ratio of water-stable macroaggregates to oven-dried initial sample minus coarse sands:

$$\text{Ima} = 1{,}000\ (\text{F}>0.2\text{-CS}) / (4\ \text{DM-CS})$$

where DM is the dry matter content of the sample determined after oven drying (at 105°C). Four replicates at least were carried out for each soil sample.

Grain size composition of samples was determined by pipette method, after organic matter destruction and total dispersion. Total carbon content was determined by dry combustion, using a LECO CHN-600 Elemental Analyzer.

Simple linear correlation coefficients were considered "highly significant" at $p<0.01$, "significant" at $p<0.05$, and "non-significant" above this value.

RESULTS AND DISCUSSION

Main data are presented on Table 1. Runoff started 20 to 30 minutes after the onset of the rainfall, and reached steady state 60 to 100 minutes after the onset of the rainfall (data not shown). Runoff depth during the initial 30 minutes of the rainfall was between 0 and 2.37 mm, and was higher in ploughed plots ($\geq$1.06 mm). Steady state runoff intensity was between 34.8 and 54.6 mm h^{-1}, i.e., 58 to 91% of rainfall depth. Instantaneous turbidity was between 5.5 and 15.7 g L^{-1} after 30 minutes of rainfall (it was considered nil on superficially tilled plot with mineral fertilizers, where runoff had not started yet) and between 6.1 and 14.9 g L^{-1} during runoff steady state. Soil loss during the initial 30 minutes of rainfall was between 0 and 31.8 g m^{-2}, and was higher in ploughed plots ($\geq$8.9 g m^{-2}). During runoff steady state, solid discharge was between 230 and 739 g m^{-2} h^{-1}, and was generally higher in ploughed plots.

Total carbon content C of the topsoil samples was between 12.8 and 18.2 g kg^{-1}, clay content between 230 and 360 g kg^{-1}. Stable macroaggregation index Ima was between 381 and 436, and was lower in ploughed plots ($\leq$400). Correlation between Ima and C was significant ($r=0.844$); correlation between clay content and C or Ima was non-significant ($|r|<0.2$).

Runoff depth and soil loss during the initial 30 minutes of rainfall displayed highly significant correlations with Ima ($r=-0.950$ and $r=-0.900$, respectively), but non-significant correlations with C (Figure 1). Early runoff and soil loss were therefore closely linked to topsoil stable macroaggregation, but not to topsoil carbon content. Instantaneous turbidity after 30 minutes of rainfall displayed significant correlation with Ima ($r=-0.759$) and highly significant correlation with C ($r=-0.904$). Steady state runoff intensity and turbidity displayed respectively

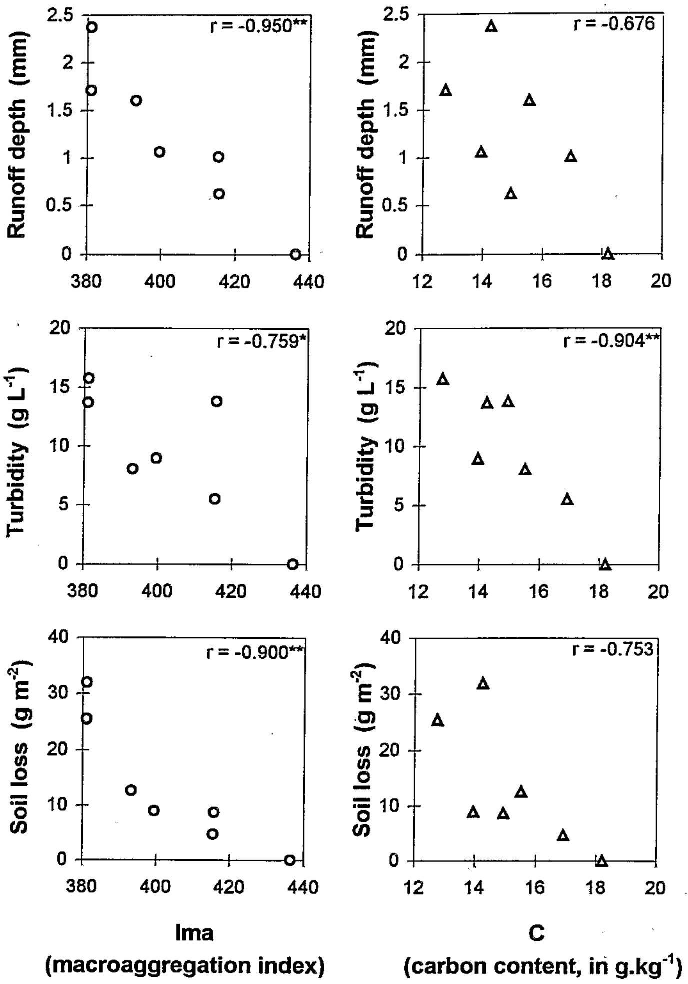

FIGURE 1. Relationships between topsoil (0-10 cm) macroaggregate stability or carbon content and runoff depth, instantaneous turbidity or soil loss after 30 minutes of simulated rainfall (*,**significant at p=0.05 and p=0.01, respectively).

significant (r=-0.788) and highly significant (r=-0.949) correlations with C, and non-significant correlations with Ima (Figure 2). Steady state solid discharge displayed significant correlation with Ima (r=-0.773) and highly significant correlation with C (r=-0.982). Steady state characterization data were therefore closely linked to topsoil carbon content.

Many authors reported negative relationships between (i) runoff or soil loss during laboratory rainfall simulation on dry soil and (ii) topsoil water-stable aggregation (after rapid immersion) or carbon content (Bryan, 1968; Luk, 1977; Reichert and Norton, 1994; Amezketa et al., 1996; Le Bissonnais and Arrouays, 1997). But few reported similar results from field rainfall simulation (Meyer and Harmon, 1984; Valentin and Janeau, 1989). Moreover, the quoted works rarely distinguished between the beginning and the end (runoff steady state) of the rainfall.

Our data did confirm the relationships between topsoil aggregate stability and field parameters of erodibility, especially runoff at the beginning of the rainfall (30 minutes): water-stable macroaggregation is known to prevent detachment of easily transportable particles, and thereby soil surface clogging and runoff (Le Bissonnais, 1996). Despite a looser relationship between macroaggregation and turbidity, initial topsoil organization also influenced soil loss at the beginning of the rainfall.

Our data also confirmed the relationship between topsoil carbon content and erodibility. Runoff water turbidity was correlated to carbon content, as reported by some authors (Feller et al., 1996). On the other hand, runoff and soil loss at the beginning of the rain were linked to a weak extent to carbon content, despite their close relationship with macroaggregate stability and the correlation between macroaggregation stability and carbon content highlighted by many authors (Tisdall and Oades, 1982; Elustondo et al., 1990; Haynes et al., 1991). The influence of carbon content was particularly clear at the end of the rainfall (runoff steady state) especially on solid discharge. This may be explained by consistency parameters such as Atterberg liquid limit, which depend on carbon content (Combeau, 1964; Rémy, 1971) and influence runoff and soil loss under wet conditions (Bryan and De Ploey, 1983; Valentin and Janeau, 1989). On the other hand, initial macroaggregate stability became less discriminative at the end of the rainfall, probably because initial organization had almost entirely collapsed due to more than 60 minutes of intense rainfall (Terry, 1998).

CONCLUSIONS

Erodibility of a cultivated Mediterranean Entisol was assessed by field rainfall simulation (60 mm h^{-1}) on 1-m^2 microplots of bare dry soil. Comparisons with laboratory analysis showed that this erodibility was linked to topsoil properties such as aggregation and carbon content. At the beginning of the rainfall simulation, there was a close relationship between runoff or soil loss and initial topsoil water-stable macroaggregation (>0.2 mm), assessed by wet-sieving after rapid immersion.

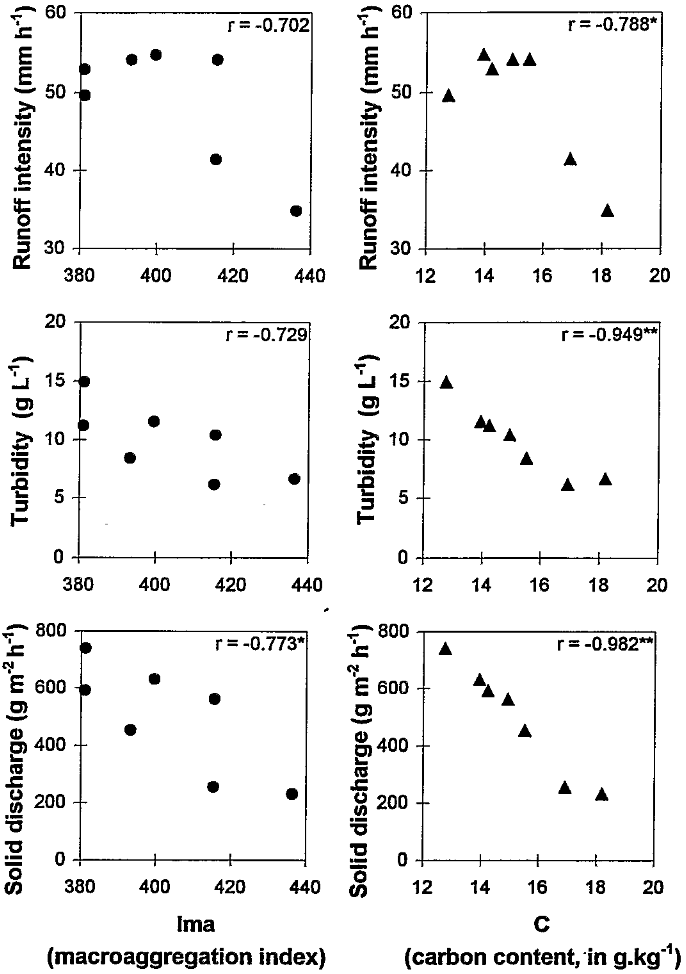

FIGURE 2. Relationships between topsoil (0-10 cm) macroaggregate stability or carbon content and runoff intensity, turbidity or solid discharge during runoff steady state (*,**significant at p=0.05 and p=0.01, respectively).

But at the end of the rainfall event (runoff steady state), runoff and soil loss were more closely linked to topsoil carbon content. This suggested that soil susceptibility to runoff and erosion under "dry" conditions (short periods of rainfall) depended on topsoil organization, but that it was influenced more by the topsoil constitution under wetter conditions. This also suggested that effects of management practices on soil erodibility depended upon their effects on topsoil aggregation and carbon content.

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