

Mecanisms and indicators of soil organic carbon action on soil structure and erodibility

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Résumé :

L'extension de la viticulture sur les coteaux méditerranéens provoque souvent une réduction des stocks de carbone du sol, entraînant une augmentation du ruissellement et de l'érosion sur des sols peu couverts par la végétation. En retour, la perte en carbone organique réduit la stabilité des agrégats du sol, qui augmente les risques d'érosion. Des indicateurs de ces processus et risques permettraient d'identifier les zones les plus vulnérables et de contrôler l'évolution de la vulnérabilité des sols. Dans le cadre de l'identification de tels indicateurs, une étude a été mise en œuvre en région méditerranéenne française, dans trois sites viticoles sur sol brun calcaire. Le premier objectif de cette étude a été de rechercher une méthode de détermination de la stabilité des agrégats adaptée aux conditions pédologiques, en testant 4 méthodes de détermination de la stabilité des agrégats basées sur l'effet d'éclatement des agrégats lors de leur humectation rapide dans l'eau, et fournissant des indices tels que le taux de macro-agrégats stables (MA200) ou le diamètre moyen pondéré (MWD). Ce test a été effectué sur des échantillons issus de 5 types d'utilisation du sol en complément de données sur l'érosion sur sol nu obtenues à partir de 14 pluies simulées d'intensité 60 mm/h. Ce premier objectif a permis de sélectionner la méthode et les indices de stabilité les mieux corrélés avec les données issues de ces pluies simulées : MA200_{LB} et MWD_{LB} dans sa forme logarithmique. Le second objectif a été d'analyser les relations entre les indices de stabilité des agrégats sélectionnés et des propriétés du sol qui peuvent être relativement aisées à spatialiser, et qui pourraient alors servir d'indicateurs spatialisables de la stabilité des sols. Dans ce but, nous avons sélectionné et analysé 68 échantillons dans des situations variées issues des 3 sites étudiés. Les relations obtenues ont montré des corrélations très significatives entre les indices de stabilité des agrégats et le taux de carbone organique, avec des ajustements significativement meilleurs avec des modèles de régression curvilinéaires. En définitive, i) les deux indices de stabilité issus de la méthode de Le Bissonnais, très significativement corrélés avec des données d'érosion simulées et ii) le carbone organique du sol qui est lui-même un bon indicateur pour la spatialisation de ces deux indices, apparaissent très utiles pour la prévision de l'évolution spatiale des stocks de carbone.

Mots clés : Carbone organique, érosion, stabilité des agrégats, comparaison de tests, encroûtements, fractions organiques, processus., Sud de la France

Abstract

The extension of vine growing on hillslopes in Mediterranean environment, may be responsible for a spatial reorganization of topsoil and his carbon stock resulting from increasing runoff and erosion phenomena when soils are uncovered or low plant covered. On the other hand, the loss of organic carbon reduces soil aggregate stability, which in turn increases erosion risks. Indicators of these processes and risks would be useful to determine the most threatened areas and to monitor the evolution of soil vulnerability. Within this framework, our objective was to test four widely used methods for aggregate stability determination, that includes slaking effects and gives indexes such as stable macro-aggregates

rates (MA 200) or mean weight diameter (MWD). The test was performed in three French Mediterranean study sites characterized by brown calcareous soils, vineyard and the existence of previous erosion data from simulated rainfalls. Our first goal was to select the aggregate stability method which was best correlated with data from simulated rainfalls. For that, we chose 5 farming situations, corresponding to 14 simulated rainfalls with an intensity of 60 mm/h. Significant relationships were found between rainfall simulation data and aggregate stability indexes. The 2 indexes resulting from the method of Le Bissonnais (MWD in its logarithmic form and MA 200) are the best adjusted with all these variables.

The second goal was to analyze the relationship between aggregate stability and soil properties that were relatively easy to spatialize. 68 soil samples on various situations of the 3 selected sites were selected and analyzed. The relationships between the 2 indexes of Le Bissonnais's method and soil properties show that there is a very significant correlation with the organic carbon rate (CSOM), while the adjustments are significantly better with curvilinear regression models. The 2 indexes of Le Bissonnais's method, that give very significant correlations with simulated erosion data and CSOM which is a good indicator for the spatialization of these 2 indexes, appears to be very useful for the forecasting of the spatial evolution of carbon stocks in the studied area.

Key words : Organic carbon, erosion, aggregate stability, crusting, organic fractions, processes.

1. INTRODUCTION

In general, soil aggregate stability is positively correlated with organic carbon content, which commonly declines under arable cropping (e.g. Haynes & Swift, 1990; Perfect et al., 1990; Le Bissonnais & Arrouays, 1997). A decrease in organic carbon content with a consequent reduction in aggregate stability in cultivated soils generally leads to soil degradation problems such as crusting, runoff and erosion (Tisdall & Oades, 1982; Elliot, 1986; Sullivan, 1990). The decrease in aggregate stability, however, is not always directly proportional to the change in organic carbon content, and the relation may vary with the method used to measure stability (Grieve, 1980; Haynes, 1993).

A well-structured soil surface exposed to successive spells of rain is subject to a series of processes that can lead to the formation of a surface crust (Le Bissonnais, 1990; Valentin & Bresson, 1992). Aggregate breakdown produces microaggregates and primary soil particles from original structural units. Their displacement and reorganization into a denser and more continuous structure forms the crust. These processes reduce infiltration rate and may increase erosion.

Measurements of organic carbon content and aggregate stability should enable us to assess the risk of structural degradation. However, such measurements are sometimes inconsistent with runoff and erosion measurements (Loch & Foley, 1994; Barthès et al., 2000). This may be because organic carbon content is not the only soil property influencing structure properties within any one types of soil. In addition, a specific fraction of the organic pool may be the main stabilizing agent, and therefore the measurement of total organic carbon content may not be sufficiently discriminating (Roberson et al., 1991; Albrecht et al. 1992; Janzen et al., 1992). Finally, the conditions during the stability test may not correspond to those in the field under rain, and there may be different processes dominating in either situation (Le Bissonnais, 1990; Haynes, 1993; Loch, 1994; Zhang & Horn, 2001).

In Mediterranean environment, the risks of reduction of soil carbon stocks by runoff and erosion increased lately under vineyard, because of the extension of vine growing on hillslopes, which intended to improve quality of the wine. A better evaluation of these risks requires the identification of runoff and soil erosion indicators that could be introduced in

spatialized models. Among these indicators, the soil aggregate stability is significant in this environment, since it can induce runoff and erosion when the soils are not covered any more by the initial vegetation. However, for the soils of this environment, such as calcareous soils, it remains to identify the most suitable indexes of soil aggregate stability (Le Bissonnais, 1996; Saidi & al, 1999). This indexes should be, at the same time, relevant with respect to runoff and erosion processes, and relatively easy to spatialize.

The objectives of this paper are: (i) to discuss the different processes by which organic carbon affects aggregate stability and erosion; (ii) to compare different laboratory methods that produce aggregate stability indexes and partly reproduce the effect of the intense rains of the Mediterranean climate on dry soils, in order to select the indexes which are best correlated with runoff and erosion data from simulated rainfalls; (iii) to analyze the relationship between the selected indexes and SOC and other soil properties.

2. MECHANISMS OF SOIL ORGANIC CARBON EFFECT ON AGGREGATE STABILITY AND EROSION

The main processes by which soils aggregates are disrupted upon rainfall are (i) slaking, i.e. the disruption of aggregates due to the forces exerted by compressed air entrapped during rewetting, (ii) differential swelling of clays, (iii) mechanical dispersion due to the kinetic energy of rain drops and (iv) physical-chemical dispersion (Le Bissonnais, 1996). Soil organic matter (SOM) is assumed to stabilize aggregates against these disruptive processes by two major actions. First, organic matter increases the cohesion of aggregates, through the binding of mineral particles by organic polymers, or through the physical enmeshment of particles by fine roots, fungal or cyanobacteria (Tisdall and Oades, 1982; Chenu and Guérif, 1991; Dorioz et al., 1993; Chenu et al., 1994; Malam Issa et al., 2001). Second, organic matter may decrease the wettability of aggregates, slowing their rates of wetting and thus the extent of slaking (Monnier, 1965; Sullivan, 1990). The second mechanism, which has received far less attention than the first one, was analysed by Chenu et al. (2000). These authors showed that organic matter associated to clay minerals increased aggregate hydrophobicity. The increased water stability of aggregates could be ascribed to better resistance to slaking, through increased hydrophobicity of the aggregates and to increased internal cohesion of the aggregates. Both clay fractions and particulate organic matter contributed to increase hydrophobicity. In addition, particulate organic matter protects the soil surface against raindrop impact and runoff and may improve infiltration through macro pores resulting from residues or biological activity.

SOM may contribute to the stability of soil aggregates by imparting them partial repellency, particularly after long dry periods. Haines & Swift (1990) reported that dried aggregates from a pasture soil rich in organic matter, were more stable than field moist ones, and that it was the opposite for arable soils with low C content.

Several organic fractions were shown to be responsible for the hydrophobicity of soils : humic acids (Roberts and Carbon, 1972; Giovannini et al., 1983; Jouany and Chassin, 1987b), aliphatic fractions (MacGhie and Posner, 1980; Ma'shum et al., 1988), or plant litter debris (MacGhie and Posner, 1981). It was shown, using model organic molecules that organic substances can render reference clays hydrophobic (Jouany and Chassin, 1987a; Jańczuk et al., 1990; Jouany, 1991). However, it has not been established to which extent natural clay organic matter associations have hydrophobic properties, nor whether they contribute to soil aggregate stability in a given climatic context. This point is particularly relevant for Mediterranean soils where dry and warm climate in summer may impart hydrophobic properties to soils. Type of breakdown process affects the intensity of aggregate breakdown

and the size distribution of soil fragments available to be detached and transported. Le Bissonnais (1996) proposed a method for measuring aggregate stability that accounts for breakdown processes by size distribution of breakdown products. Three of these breakdown processes - slaking, differential swelling, and mechanical breakdown – are simulated by diagnostic tests. In the context of Mediterranean soils slaking can be identified as the main process that could be affected by hydrophobicity imparted by SOM.

3. MATERIALS AND METHODS

3.1. Study sites

Three representative study sites with brown calcareous soils, were selected within the Mediterranean from previous studies :

The site of **Pradel** is localised in Ardèche (southern of the Rhone-Alpes region, France), at an altitude of 250 meters, on a scrap of erosion glacis. The substratum is a calcareous marl supporting a layer of colluviums. The experimental set up consists of runoff plots under vine, with an average slope of 10%. The brown calcareous soil (brown calcic cambisol), about 1 meter thick, have a silty-clay texture. Annual average precipitations are 1000 mm, and their mediterranean rhythm frequently provides intensities higher than 50 mm/h (Maillo, 1999).

The site of **Corconne** is located in Gard, in the North of Montpellier (Languedoc Roussillon region, France). The landscape is covered by scrubland and vineyards. It includes an argillaceous sedimentary basin with limestone conglomerates, at an altitude ranging between 100 and 120m. This basin is overhung by small limestone hills slightly undulating with slopes from 10 to 20%. For this study, 4 stations representative of these conditions were selected. The calcareous soils of these stations (calcaric regosols and brown calcic cambisols), 0,4 to 1,5 meter thick, have a silty-clay texture. Annual average precipitations are 1100 mm, and the decennial rainfall intensities are from 55 to 60 mm/h during one hour (Arshad & al, 1999).

The site of **Roujan** is located in Hérault, in North East of Béziers, about 60 km west of Montpellier (Languedoc Roussillon region, France). It is a small wine-growing catchment of 91 ha, which is used for experimental studies by the soil science laboratory of the French National Institute of Agricultural Research (INRA) from Montpellier. The soil texture varies according to the position in the slope. On uneven of 50 meters one finds stony chromic luvisols (quartz and limestones) in summit position, loamy calcaric regosols on anthropic terraces in midslope position, loamy calcic cambisols in footslope position, and clayey gleyic cambisols downslope (Andrieux & al, 1993). Annual average precipitations are 650 mm and the rainfall intensity of storms exceeds 30 mm/h , with instantaneous intensities that can reach 200 mm/h (Andrieux & al, 1997). For this study, the soil samplings were carried out on the loamy calcareous soils in midslope and footslope position.

3.2 Experimental set-up

For establishing the relationships between aggregate stability indexes and several rainfall simulation variables, we chose 5 farming situations distributed on the stations of Corconne and Pradel (tab. 1). In Corconne village : two parcels of chemically weeded vineyard, planted in 1996 (5 y. old) and 1980 (21 y. old), and a parcel in long duration grassy fallow, weeded for the experimentation. (25 y. old). In Pradel, the two situations selected are parcels of weeded vineyard, one chemically (25 y. old) and the other mechanically (25 y. old). Data on runoff and erosion were obtained with 14 simulated rainfalls including repetitions, with an intensity of 60 mm/h (Tab.1). These rains were carried out on plots of 1 m² with an Orstom-

Sites and Stations	Average annual Raifall	Average slope %	Farming situations	Simulated rainfalls (60 mm.h ⁻¹ on 1 m ² plots)	Methods of characterization of soil aggregate stability
Corconne village (calcareous brown soil)	1100 mm	6%	25 years old grassy fallow (soil covering = 100 %), succeeding a vineyard.	2 replicates	Slaking treatments on dry sized aggregates according to: Yoder (1936) Hénin (1958), modified with water
			5 years old vineyard (young vineyard), Syrah variety, chemically weeded inter-rows.	3 replicates	
			21 years old vineyard, Merlot variety, chemically weeded inter rows. The vine shoots are crushed and left on the soil.	3 replicates	
Pradel (calcareous brown soil)	1000 mm	13%	25 years old vineyard, Syrah variety, chemically weeded inter rows.	3 replicates	Kemper & Rosenau (1986) Le Bissonnais (1996)
			25 years old vineyard, Syrah variety, mechanically weeded inter-rows on a 10 centimetres depth.	3 replicates	

Table 1. Farming situations and protocol used for the 1st phase of the study

Situations	Sites	Number of samples
Garrigue	Corconne	11
Grassy fallow	Corconne	4
Bare soil prepared for vineyard	Corconne	4
Spoil earth from vineyard preparation	Corconne	1
Weeded vineyards	Corconne, Pradel, Roujan	45
Vineyard with mulch of straw	Pradel	1
Weeded vineyards	Roujan	2
	Total	68

Table 2. Situations and soil samples used for the 2nd phase of the study

Stations	Situations	Clay g/kg	Silt g/kg	Sands g/Kg	E.G. g/Kg	OM g/Kg	CaCO ₃ g/Kg	pH water
1. Corconne village	Garrigue (2)	327	510	163	226	52	556	7.7
	Fallows	353	494	153	88	49	523	7.7
	Vine	405	392	203	97	9	552	7.9
2. Pradel	Vine	341	413	246	132	27	342	7.7
3. Roujan	Vine (2)	180	414	406	33	15	309	Nd

Abbreviations used : E.G : gravels. OM : organic matter (2) : situations used for the 2nd phase of the study.

Table 3. Physico chemical topsoil properties (0-5cm) of the 3 selected stations

type rainfall simulator, with a metering and mobile jet that generates rains of intensity ranging between 10 and 150 mm/h (Asseline and Valentin, 1978). Under vine, the rains were carried out in the inter-rows. In addition, 38 soil samples were taken from the topsoil layer (0-5 cm) of the 5 selected situations, for measurements of soil aggregate stability and for physico-chemical analysis. From the hydrographs and turbidigraphs analysis, we obtained the following variables: **RBR** = rainfall before runoff initiation ; **KRU30** = runoff ratio during 30 mn. ; **KRIPAL** = instantaneous runoff ratio at equilibrium runoff rate (hydrograph's plateau) ; **TURBIPAL** = running water turbidity at equilibrium runoff rate ; **TURBI30** = turbidity with 30 mn ; **ERO30** = soil losses during the first 30 mn of simulated rainfalls. To meet our second aim, i.e. the relationship between selected indexes and soil properties, the whole of 68 topsoils samples were carried out on various situations of the 3 selected study sites (Tab 2).

3.3. Soil samples analysis

The 38 samples of soil selected for the first phase of the study were the subject of aggregate stability analysis according to 4 methods of which the common treatment is a slaking effect, by bursting of dry samples during their fast immersion in deionised water (Le Bissonnais and Le Souder, 1995). Principal specificities of these methods are as follows:

- *Method of Yoder* (Yoder, 1936) : 80g of the 3150-5000 μm soil fraction are poured on a column of sieves, which is immersed in water. The classes of aggregates are separated by sifting in water using the Yoder apparatus (amplitude 33 mm, frequency 30 cycles/mn, duration 30 mn). After drying, an aggregate size distribution curve is obtained, for aggregates between 0.1 and 5000 μm .

- *Method of Hénin* (Hénin & al., 1958) modified with water : 10g of the 0-2000 μm soil fraction are poured on a 200 μm sieve, which is immersed in water. The water stable aggregates > 200 μm are separated from the remainder of soil with the apparatus of Féodoroff (amplitude 40 mm, frequency 60 cycles/mn, duration 30 seconds).

- *Method of Kemper & Rosenau* (Kemper & Rosenau, 1986). 4x4g of the 500 -2000 μm soil fraction are poured on a 200 μm sieve, which is immersed in water. The stable fraction > 200 μm is separated from the remainder of the sample by using the apparatus of Kemper and Koch (amplitude 13 mm, frequency 35cycles/mn, duration 6 mn).

- *Method of Le Bissonnais* (Le Bissonnais, 1996a). 5x10g of the 3150-5000 μm soil fraction are poured on a 200 μm sieve, which is immersed in water. The fraction > 200 μm is stabilized with ethanol before being dried and gently sifted. The aggregates size distribution < 200 μm is obtained by laser diffraction. An aggregate size distribution curve is obtained, for aggregates between 0.1 and 5000 μm .

For each of the 4 methods, coarse sands (200 -2000 μm) were separated from the aggregates by chemical dispersion and ultra sounds. A first type of aggregates stability index, the rate of aggregates > 200 μm (MA200) were then calculated. For the methods of Yoder and Le Bissonnais, which give the particles size distribution in the range 0.1-5000 μm , the results gave also the mean weight diameter, either without coarse sands and gravels (**MWD**) or by counting the latter (**MWDG**).

Furthermore, three potential factors of the aggregate stability in calcareous soils were analyzed on the whole 68 samples : the organic carbon rate, the texture and the content of CaCO_3 (Le Bissonnais and Le Souder, 1995, Le Bissonnais, 1996b). Organic carbon rate was determined by elementary microanalysis CHN on samples crushed in particles < 200 μm , after removing of carbonates by samples acidification. The content of CaCO_3 was deduced from the difference between carbon rates before and after the samples acidification. Finally, the particles size analysis were carried out by laser diffraction (Laurent and Albrecht, 1993).

3.4. Statistical calculations

The study of the relations between the aggregate stability indexes and the variables resulting from the simulated rains led i) to the neperian logarithmic transformation of MWD variables ($\log(\text{MWD}+1)$), in order to obtain quasilinear functions between these indexes and the MA indexes, and ii) to adopt the neperian logarithmic form of erosion within 30 minutes ($\log(\text{ERO30}+1)$), in order to improve the adjustments. The research of the best functions of adjustment between the aggregate stability indexes and the variables of simulated rainfall was carried out with the nonlinear regression module of Statistica 5.5 © software (StatSoft Inc.), by associating the simplex and Newton methods of convergence. To obtain an overall assessment of the intensity of the relations between each aggregate stability indexes and the whole of the variables of simulated rainfall, we calculated, from the best models of regression obtained, a synthetic coefficients of correlation (r_{syn}), defined by equation 1 :

$$r_{\text{syn}LAGi} = \sqrt{\frac{\sum_{j=1}^{j=n} r_{\text{Pearson}}(LAGi, yj)^2}{n}} \quad (\text{eq. 1}), \quad \text{where } r_{\text{Pearson}} \text{ is a Pearson coefficient of correlation, } LAGi \text{ is an index of aggregate stability, } yj \text{ a variable of simulated rainfalls, and } n \text{ is the number of variables of simulated rainfalls.}$$

To validate the assumption resulting from these synthetic coefficients, we calculated the sum of the probabilities of difference between the r_{Pearson} coefficients of a selected aggregate stability index and the other ones for each variable of simulated rainfall, with a standard procedure of statistical comparison by couples of r coefficients.

4. RESULTS

4.1. Physicochemical properties of topsoil

Table 3 Results indicates the prevalence of CaCO_3 contents in the topsoil (0-5 cm) of all the studied stations (Table 3). Silty clay textures of the stations of Corconne and Pradel are similar, but the topsoil of the station of Roujan has a more sandy texture. The organic matter content under vines are clearly lower than those under fallow.

4.2. Relationships between rainfall simulation and aggregate stability indexes

Table 4 presents the averages, in the 5 selected situations, of : i) the runoff and erosion data obtained from simulated rainfalls, and ii) the aggregates stability indexes. One can note that the situations that have the highest aggregate stabilities (fallow, and secondarily mechanically weeded vine) have also the highest rainfall before runoff initiation (RBR), the lowest runoff coefficients (lowest KRU30, KRIPAL) and the lowest soil losses (lowest $\log(\text{ERO30}+1)$). Furthermore, no significant relationships were found between the aggregates stability indexes and the turbidity variables (TURBI30 and TURBIPAL), but significant relationships were established between these aggregate stability indexes and the other rainfall simulation variables. Table 5 presents only the significant relationships found, with the r_{Pearson} values and the associated regression models. The relationships are positive and linear in case of the RBR variable; they are negative and curvilinear or linear in case of the other runoff and soil losses variables. The values of the synthetic coefficient r_{syn} (c.f. § 3.4 for r_{syn} definition) appear in the last line of this table. These values are represented on a histogram in figure 1. They show that indexes resulting from the method of Le Bissonnais - MA200 and MWD in its logarithmic form - are the indexes best adjusted with the runoff and soil losses variables, which has been confirmed by the statistical comparison by couples of r coefficients.

Simulated and Soil Aggregate Stability indexes			Corconne Village			Pradel	
Rainfall variables			Grassy Fallow	Young weeded Vineyard	weeded Vineyard	Chemically weeded Vineyard	Mechanically weeded Vineyard
Simulated Rainfall variables	Runoff	RBR mm	42	9	9	10	21
		KRU30 %	0	38	26	27	4
		KRIPAL %	0	82	88	86	36
	Soil losses	TURBI30 g.l ⁻¹	/	6	4	4	4
		TURBIPAL g.l ⁻¹	/	7	2	3	5
		ERO30 g.m ⁻²	0	76	29	40	3
Soil Aggregate Stability Indexes	Le Bissonnais	MA200 LB %	91	37	33	42	55
		MWD LB µm	3730	136	132	156	245
	Yoder	MA200 YOD %	93	35	33	24	37
		MWD YOD µm	3940	135	135	53	85
	Henin	MA200 HEN %	73	32	28	35	30
	Kemper & Rosenau	MA200 KEM %	83	24	21	37	31

Abbreviations used : Rainfall simulation variables : see § 3.2. Soil aggregate stability indexes : see § 3.3; the suffixes indicate the methods used : **LB** for Le Bissonnais, **YOD** for Yoder, **HEN** for Hénin, and **KEM** for Kemper & Rosenau.

Table 4. Averages of the simulated rainfall variables and the soil aggregate stability indexes for the 5 selected farming situations.

y (simulated rainfall variables)	N x (soil aggregate stability indexes)								
	b logMWD GLB+1	MA200 GLB	LogMWD LB+1	MA200 LB	LogMWD YOD+1	MA200 YOD	MA200 HEN	MA200 KEM	
	Coefficient of correlation (rpearson):								
RBR (r > 0)	1 0,967* 2 **	L 0,945** *	L 0,945** *	L 0,961** *	L 0,772* *	L 0,880* **	L 0,830* **	L 0,852** *	L
KRU30 R < 0)	1 0,809* 4 **	C 0,791** *	C 0,830** *	C 0,787** *	C 0,454ns L	C 0,565* C	C 0,488ns L	C 0,589* C	C
KRIPAL(r < 0)	1 0,967* 4 **	C 0,962** *	C 0,968** *	C 0,962** *	C 0,719* L	C 0,944* **	C 0,743* *	L 0,780** L	L
Log(ERO30+1) (r < 0)	1 0,901* 4 **	C 0,886** *	C 0,914** *	C 0,883** *	C 0,580* L	C 0,698* *	C 0,611* L	L 0,687** L	L
	Synthetic coefficient of correlation (rsyn):								
All y variables	0,920	0,907	0,923	0,908	0,615	0,762	0,657	0,718	
Abbreviations used : ns=non significant; *, **, ***=significant with the threshold of 95%, 99% and 99,9% L=linear model of regression; C=curvilinear model of regression (logistic)									

Table 5. Coefficients of correlation between soil aggregate stability indexes and simulated rainfall variables.

y (aggregate stability indexes)	Nb. of samples	x (Physico-chemical properties)					
		CSOM	CLAY	A+LF	SILT	SAND	CaCO ₃
Log(MWDLB+1)	68	0,822***L 0,917***C	0,252*L	0,230nsL	0,431***L	-0,412***L	0,004nsL
MA200LB	68	0,839***L 0,912***C	0,325**L	0,344**L	0,434***L	-0,470***L	-0,072nsL
Abbreviations used : ns: non significant ; *, **, ***= significant with the threshold of 95%, 99% and 99,9% L= linear models C= curvilinear models (CSOM and MA200LB in g.100g ⁻¹ ; MWDLB in µm):							

Table 6. Relations between the soil physico-chemical properties and the two selected soil aggregate stability indexes

4.3 Relationships between aggregates stability indexes and topsoil properties

Data of table 6 were obtained from the 68 soil samples available, and the two aggregate stability indexes of the method of Le Bissonnais that are best correlated with the rainfall experiment variables. This table presents the relationships between these two stability indexes and the organic carbon rate (CSOM), the texture and the CaCO_3 content. These stability indexes vary in a very significant way with the organic carbon rate ($r_{\text{Pearson}} = 0.917$ for the MWD; and 0.912 for the MA200), while the adjustments are significantly better with curvilinear regression models ($p > 95 \%$). The curvilinear model for MWD is given by equations 2:

$$\log(\text{MWDLB} + 1) = 4.83 + \frac{2.76}{1 + 7 \cdot 10^8 \cdot e^{(-1.01 \cdot \text{CSOM})}} \quad (\text{eq. 2})$$

The relationships between texture and these aggregate stability indexes appear weaker ($|r| < 0.45$). However, a thorough analysis of the data reveals that for situations with low organic carbon content ($< 10 \text{ g.kg}^{-1}$), 70% of the increase in soil aggregate stability is explained by the increase in clay contents. Lastly, the relationships between texture and CaCO_3 contents are not significant.

Figure 2 shows the “S” shape of the relationship between CSOM and the stability index of the 68 soil samples. It shows the existence of a threshold, located between 20 and 25 g.kg^{-1} of CSOM, below which the aggregate stability index is low (MWD ranging from 100 to 200 μm). Beyond this threshold, the aggregate stability index reach quickly high values (MWD ranging from 1000 to 3500 μm). This threshold separates vineyards (low CSOM) from “garrigue” and fallow (high CSOM).

5. DISCUSSION

The results show in particular that runoff rates can reach high values (tab 4). This reproduces what occurs generally in Mediterranean landscape, where runoff frequently initiates catastrophic floods and pollution, and is a very active process. The total soil losses within the first 30 min of simulated rainfalls are relatively low, but these soil losses, which represent only the interrill erosion, can be rich in organic matter. Moreover, the observed high runoff rates can also initiate a substantial rill erosion which could be measured by other methods than rainfall simulation (Asseline & al., 1993).

Furthermore, these results bring two sets of information, which are discussed below.

5.1 relationship between aggregates stability indexes, runoff and soil losses under simulated rainfalls

Most of the relations calculated between the stability indexes and the variables of rainfall simulations referring to the runoff and the soil losses into 30 min are significant. This joins the conclusions of other studies carried out under simulated or natural rainfalls (Barthès and al., 2000). The lack of relationship between these indexes and the turbidities variables is not surprising, and it can be explained by the creation of natural water puddles in the soil surface micro depressions, which induce some irregularities in the water flow.

The indexes resulting from the method Le Bissonnais (1996) seem particularly interesting, as runoff and erosion indicators, since they are better correlated with the rainfall simulation variables than the indexes resulting from the other methods. On one hand, the preparation of the samples (aggregates up to 5000 μm , and soil weights of 50 g) used for this method cannot be the only causes of these differences, although it probably improves the representativeness of the samples, compared to the methods of Hénin (1958) and Kemper & Rosenau (1986). Indeed, the sample preparation in the method of Yoder (1936) is similar, although this method does not provide excellent correlations in this study. On the other hand, a significant

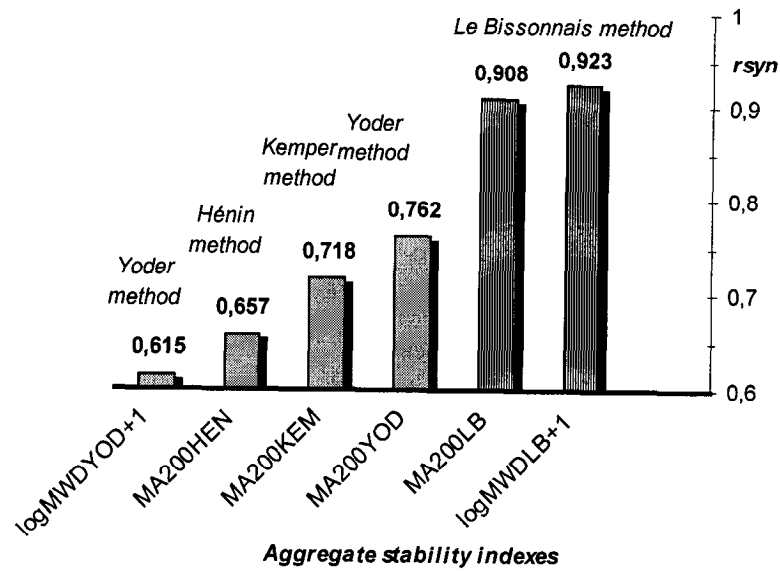


Figure 1. Comparison of the synthetic coefficients of correlation (r_{syn}) between eight soil aggregate stability indexes and 5 rainfall simulation variables (data from table 5)

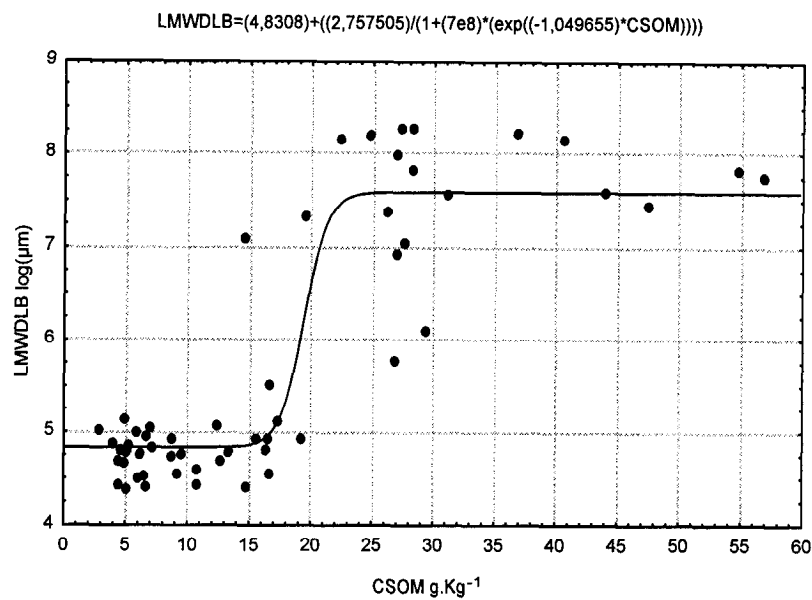


Figure 2. Relationships between CSOM and aggregate stability measured using Le Bissonnais's method (MWDLB)

improvement seems to lie in the disappearance of mechanical agitation added to the slaking treatment, which is specific to the method of Le Bissonnais, and which reproduces probably in a better way the conditions under rainfalls.

A complementary interest of this method results in the fact that it can take account of the gravels, which are frequent in the Mediterranean soils, insofar as the correlations obtained by integrating coarse sands and gravels are almost as good as by withdrawing these elements.

In addition, compared to the methods of Henin and Kemper & Rosenau, the soil aggregate stability index provided by this method give a more complete information about the aggregates size distribution, by the taking into account of the MWD (Amezketta and al., 1996).

5.2 Relationships between soil aggregate stability indexes and topsoil properties.

The results presented in table 6 and figures 2, show, for the 68 studied situations, that the soil aggregate stability is strongly correlated to the organic carbon rate (CSOM rate). The organic matter thus appears as a predominant indicator of the aggregate stability. Although organic matter's role is variously explained by the authors, one of the most frequent explanations is the protective role of organic matter against the slaking effect (Le Bissonnais & Singer, 1993; Le Bissonnais & Le Souder, 1995; Barthès & al, 1999; Saïdi & al, 1999; Six & al, 2000). It is thus probable that organic matter is not only an indicator, but also a determining factor, without which the soil aggregate stability could not be maintained (Jacquin, 1978; Six and al, 2000).

From these results, it appears possible to estimate the MA200 or MWD indexes obtained by the method of Le Bissonnais from the carbon organic rate in the type of calcareous soils studied. However, the results show that the texture effect cannot be neglected for situations with low CSOM rate. Lastly, the lack of correlation between aggregate stability and CaCO_3 contents do not indicate the absence of stabilizing role of CaCO_3 , but more probably that this role is not discriminating in the range of the studied soil samples.

6. CONCLUSION

From this study, it may be advisable to retain, as runoff and erosion risk indicator, the aggregate stability index resulting from the method suggested by Le Bissonnais (1996), which minimizes mechanical agitation after slaking treatment on sized aggregates. Indeed, pedotransfer functions link narrowly this index to the sensitivity of soils to runoff and interrill erosion, on the one hand, and to the organic carbon rate (CSOM rate) on the other hand.

Insofar as the spatial variability of the CSOM rate can be evaluated by various methods (Bourgeon, 1999; Arrouays and al., 1998; Chen and al., 2000), CSOM appears as a good indicator for the spatialization of the soil stability index. Furthermore, as runoff and interrill erosion are two major factors of the spatial evolution of carbon stocks, it appears possible to propose, for the studied area, the implementation of a procedure which integrates the selected soil aggregate stability index, for the forecasting of the spatial evolution of carbon stocks : the first phase of this procedure, starting from the pedotransfer functions, would consist in the acquisition of the organic carbon rate spatial variability, in order to evaluate the spatial variations of the selected index. In a second phase, the evaluation of the spatial variations of the soil stability index could be integrated in a forecasting model of erosion risks, in combination with other factors of runoff and erosion such as slope, climate, and plant cover within the studied area (Le Bissonnais and al., 2001). Lastly, this evaluation of the spatial variations of erosion risks could be integrated into the forecast of the spatial evolution of carbon stocks in the studied area.

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