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"Agricultural Nonpoint Source Pollution: Model Selection and Application"

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Agricultural Nonpoint Source Pollution: Model Selection and Application

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SOME ASPECTS OF SOIL EROSION MODELLING

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ABSTRACT

Soil erosion is often accelerated by agricultural activities. As sediment acts both as pollution factor and pollutant carrier, soil loss can be considered a non-point pollution process. An experiment on splash detachment and runoff transport shows that interrill erosion depends on the runoff transport capacity or on the detachment rate following which one is the limiting agent. Mathematical description of these processes indicates that statistical equations are inadequate to describe interrill erosion. A residual variability of the data may be attributed to dishomogeneity at the soil surface (aggregate and clod distribution, crusts, etc.). This variability can induce errors in the estimate of soil loss. Consequently, it should be predicted as it can assume a relevant role when the damages due to pollution depend on critical thresholds.

INTRODUCTION

Soil erosion by rain is a natural phenomenon; it can be accelerated by human activity such as agriculture. It has some negative effects on the environment, which can be categorized as fertility loss and pollution.

Fertility loss depends on the fact that erosion usually takes place on the most superficial soil layer, which is the best structured and the richest in nutrients. The fraction of the detached material which is transported by superficial runoff to the channel system may cause excessive silting when deposited. Moreover, large quantities of sediments generally cause disequilibria in the aquatic environment. Sediment is usually rich in chemicals due to nutrients, herbicides, etc., present in the soil. Consequentely, sediment also contributes to chemical pollution.

The study and control of the erosive processes are primarily relevant where agriculture is associated to a high risk of erosion or where the soil is rich in the clay, silty-clay fraction, that is very effective in trapping chemicals.

The prevision of pollution and the control of pollutant factors can be achieved through models of different kinds (such as statistical, deterministic, etc.). Their prevision should be performed on a single rainstorm basis as pollution is a discontinuous phenomenon which is often linked to critical values not to be surpassed.

EROSION STUDIES IN ITALY

Italy is characterized by a high erosion potential (hilly and montaneous agriculture) and by soils rich in clay (20% ca. of the agricultural territory). Aggressiveness of the climate and excessive antropization make erosion control pertinent to pollution. Unluckily, climatic differences make erosion difficult to be studied. Roster [1], divided Italy into five climatic areas; a simple analysis of the season - to - season variation of precipitation is enough to subdivide Italy into three zones (one peak of precipitation in winter, one peak in summer, two peaks in spring and autumn).

Those climatic differences might have influenced the results of the studies on soil erosion performed in Italy as data were usually analysed on a single rainstorm basis while using statistical techniques.

The erosivity index proposed by Wischmeier and Smith [2] was found to be both well correlated [3,4] and uncorrelated [5,6] to erosion. Aggressiveness indices depending on runoff characteristics only [3,7] or on both rain and runoff [6,8,9,10] were also proposed. Only once was an additive index (rain + runoff) compared to erosion [3].

Few data allowed a complete comparison between measured erosion and estimations made through the Wischmeier and Smith's equation [11]: a slope effect described through a convex parabola was successfully investigated in Sicily [4] while an over-stimation of soil loss was observed for clayey soils [12].

The above mentioned results, more completely summarized by Chisci et al. [13] only approximatively indicate the erosion hazard in environments very similar to those in which the equations were developed. Moreover, statistical equations are usually not physically based as pointed out by Kirkby [14]. Consequentely they generally fail when used to predict erosion values close to extremes of the tested range. An example of how even a single aspect of erosion cannot be easily described is presented in the following paragraph.

AN EXPERIMENT ON SPLASH DETACHMENT AND RUNOFF TRANSPORT

1: Scientific background

When a drop hits the soil surface it splashes detaching particles and aggregates. The mechanism of splash detachment has been studied by many researchers [15 to 37]. The main features through which a drop detaches particles [15,16] are as follows:

a - a drop hits a soil particle releasing a part of its momentum to it;

b - a drop, during the impact, generates a corona of lateral jets of water. The shear stress produced across the solid-liquid contact area determines the detachment of particles.

The fact that a film of water develops at the soil surface can cause a reduction of the detached material. In fact it resists the expansion of the jets and reduces their speeds [17]. Moreover, the drop impact is partially dissipated into the water film [18]. On the other hand, an increase of the pore water pressure within the aggregates might increase detachment [19,20]. Some researchers [21] observed an initial increase followed by a decrease in detachment as the height (h) of the water film increases. The value of h at which the detachment reaches its maximum was estimated to be between 0.14 and 0.20 times the diameter of the hitting drop. On the contrary, other researchers observed a continuous decrease of detachment with increasing h [22,23,24,25].

As proposed by different authors [26 up to 34], indices of detachment power of rain are the kinetic energy or the momentum or the instantaneous intensity of rain or factors as m^a v^b where m is the mass of the rain drop, v its speed and a and b empirical exponents. In addition, slope has showed a positive effect on detachment [28,31,35]. Also the angle between the trajectory of rain-drops and the slope might effect detachment [36,37].

The detached material can be transported by the runoff or by saltation due to the drop impacts. The runoff transport role depends on the equilibrium between the runoff transport capacity (TC) and the detachment rate (DR). If DR is greater than TC the transported material cannot exceed TC. When the opposite situation takes place, the transported material cannot exceed DR. The passage from one situation to other can be abrupt [28] or gradual [31].

ii: Materials and methods

The experiment was planned in such a way to have:

1 - detachment rate due to raindrop impact only;
2 - raindrop splash transport excluded from the measurement of soil loss.

TAB. I : Textural and aggregate distribution (in %) of the soil samples (vertic xerochrepts).

SIZE	TEXTURE	AGGREGATE initial*	AGGREGATE splashed-out**
μ	%	%	%
4000	-	100.0	100.0
2000	100.0	93.3	99.6
1000	99.6	83.8	97.6
500	99.5	76.1	94.3
250	99.2	67.5	89.0
125	98.7	60.3	83.6
63	96.2	54.0	78.3
30	94.1		
15	89.4		
5	78.7		
2	60.4		
1	48.2		

* - Distribution of aggregate after to 24^h of saturation by capillary rise.
** - Average distribution of aggregate splashed-out during the tests.

The reduction of the runoff detachment to a negligible value (Condition 1) was achieved using a cohesive soil (Tab.1). It has also been controlled if high runoff rates, in absences of rain, produced erosion. Condition 2 was achieved shielding the runoff collector.

Soil samples were 10 cm deep and 50 cm wide; slope and lengths were variable: from 0.5 to 2 m and from 5% to 30% respectively. The samples were prepared using air dried soil, passed through a 4.0 mm sieve [38]. The initial water content was 4.5% (air dried) or 38% (48h of saturation by capillary rise).

The caracteristics of the simulated rains were as follows:
intensity: 15, 30, 60, 110 mm h^{-1};
median drop diameter: 1.9 mm;
kinetic energy per unit of mass of rain: 24.1 Joule kg^{-1}.
Drop sizes and kinetic energy per unit of mass of rain were kept constant in all the runs.

Additional runoff (clear water) was supplied from upslope during some runs. The runoff speed and the height of the water film were calculated using the programme proposed by Savat [39].

iii: Experimental results

The data taken into account correspond to constant rate of runoff and soil loss. Using steady state data the variability due to initial breakdown of aggregates [19,20] is reduced.

The ratios A/i, where A is the measured soil loss in g min^{-1} m^{-2} and i is the rain intensity in mm min^{-1}, are drawn versus the height of the film of water in Fig.1a. The observed behaviour agrees fairly well with the one described by Mutchler and Young [21] even if there is a subdivision due to slope. The experimental data allow two interpretations:

1 - Differences in detachment rate depend on the effect of the film of water;
2 - Soil loss is controlled by the transport capacity until the maximum is reached, then by detachment rate.
According to 1 -, the detachment rate can be described by the following equation:

$$DR = 3800\ I \sin^{0.32}\gamma\ h^{1.9} \exp(-6.8\,h) \qquad (1)$$

where:
DR = detachment rate (g min^{-1} m^{-2})
h = average height of the water film along the plot (mm)
= slope angle.

This hypothesis is not completely satisfying as it clashes against the data produced by Ghadiri and Payne [22]. Moreover, there is no detachment at zero slope.

A function depending only on runoff characteristics is required to support hypothesis 2. This function, which is an estimation of the runoff transport capacity, must verify the following condition:

$$A/TC = \text{constant when } h<h_{cr} \qquad (2)$$

where:
h_{cr} = value of h at which the ratio A/i is maximum.

A function approximating condition (2) is as follows:

$$TC = 120wqv^{1/2} \qquad (3)$$

where:
TC = transport capacity (g min^{-1})
w = width of the plot (m)
q = runoff discharge rate per unit of width (cm^{2} s^{-1})
v = runoff speed at the bottom of the plot (cm s^{-1}).

The ratio A/TC versus h is drawn in Fig.1b. It is possible to observe a certain constancy when h is smaller than h_{cr} while the slope does not separate data anymore. The decrease, which follows, indicates that the detachment is already the limiting factor. This result supports hypothesis 2.

Park et al. [15] used an exponential function to describe the effect of the height of the film of water on the detachment. Using the same kind of function and taking into account the slope angle - even if data are not enough to state any relation for sure - the detachment rate can be expressed as follows:

$$DR = 160(\sin^{0.77}\gamma + 0.22)\exp(-3.07h) \qquad (4)$$

The exponent of the slope and the additive term fairly well agree with the values suggested by Khaleel et al. [31].
An estimate of erosion can be performed using equation (3) when TC<DR and equation (4) when DR<TC (Fig.2). The data show a scattering which is larger than the estimate of the maximum error due to the measuring apparatus. Actually, data should not scatter more than 10% from the 45 sloping straight line. On the contrary the 50% of the data scatter more than the 20%. This indicates that there are sources of variability not included in equations (3) and (4). As moisture content, shear strength, cohesion, bulk density showed correlation with the residual variability other sources of variation must be taken into account such as differences in aggregate distribution at the soil surface [20].

CONCLUSION

The experiments on splash detachment and runoff transport showed that:

1 - two equations are needed to explain soil loss;
2 - detachment rate shows an exponential decrease with the height of the water film;

3 - a residual variability exists which may depend on surface dishomogeneity of aggregate distribution.

Item 1 and 2 indicate that a statistical equation is inadequate to describe interrill erosion. Item 1 clearly states that two equations are needed while item 2 limits severely the use of statistical techniques. In fact, the detachment rate cannot be approximated by a single equation over its entire range of variation because of the exponential. Moreover, rain intensity, soil characteristics, length and slope of the interrill are also implicitly present in the detachment equation as they can predict the height of the water film. The effects of the mentioned factors cannot be easily separated as the usual regression equations require.

The residual variability due to superficial dishomogeneity (aggregates, clods, crusts, etc.) might last in natural conditions affecting the estimates of soil loss. It should be, consequentely, predicted to define the probability levels of the erosion estimates which is relevant when pollutant contents must be kept under critical values.

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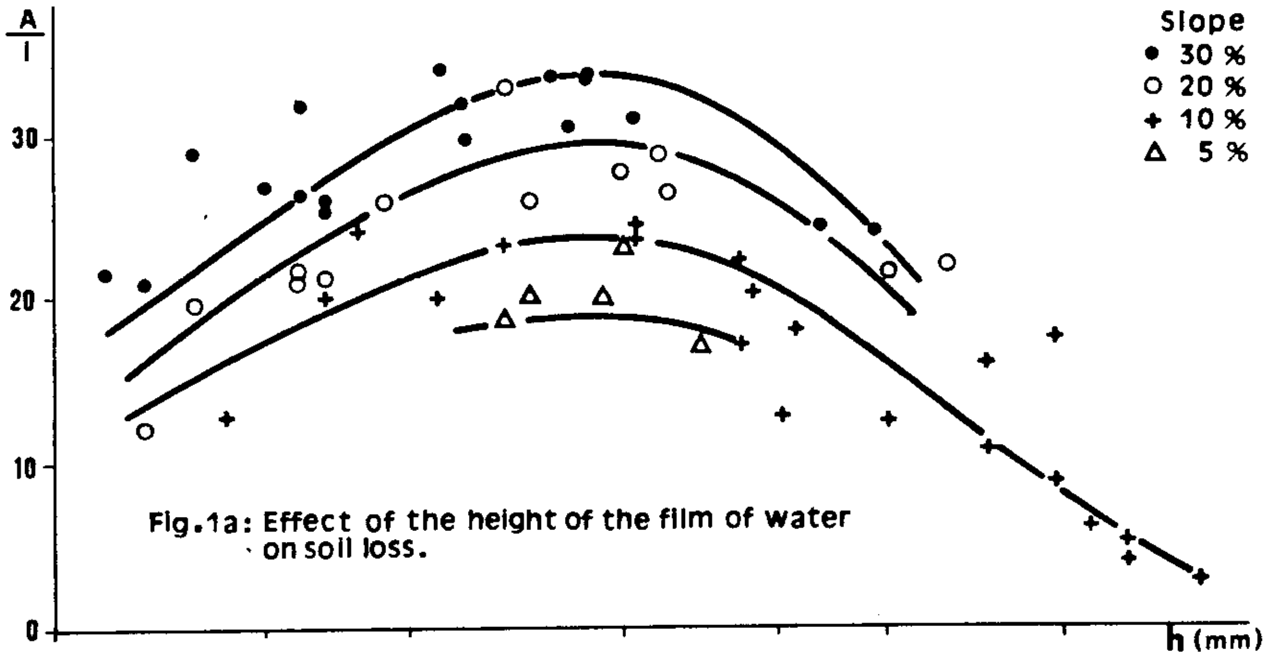

Fig.1a: Effect of the height of the film of water on soil loss.

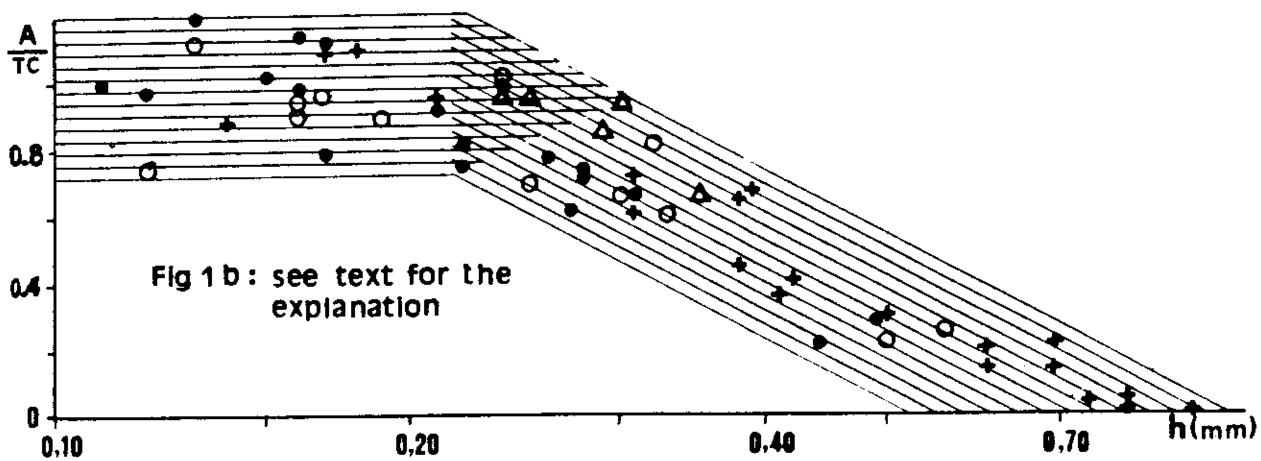

Fig 1 b: see text for the explanation

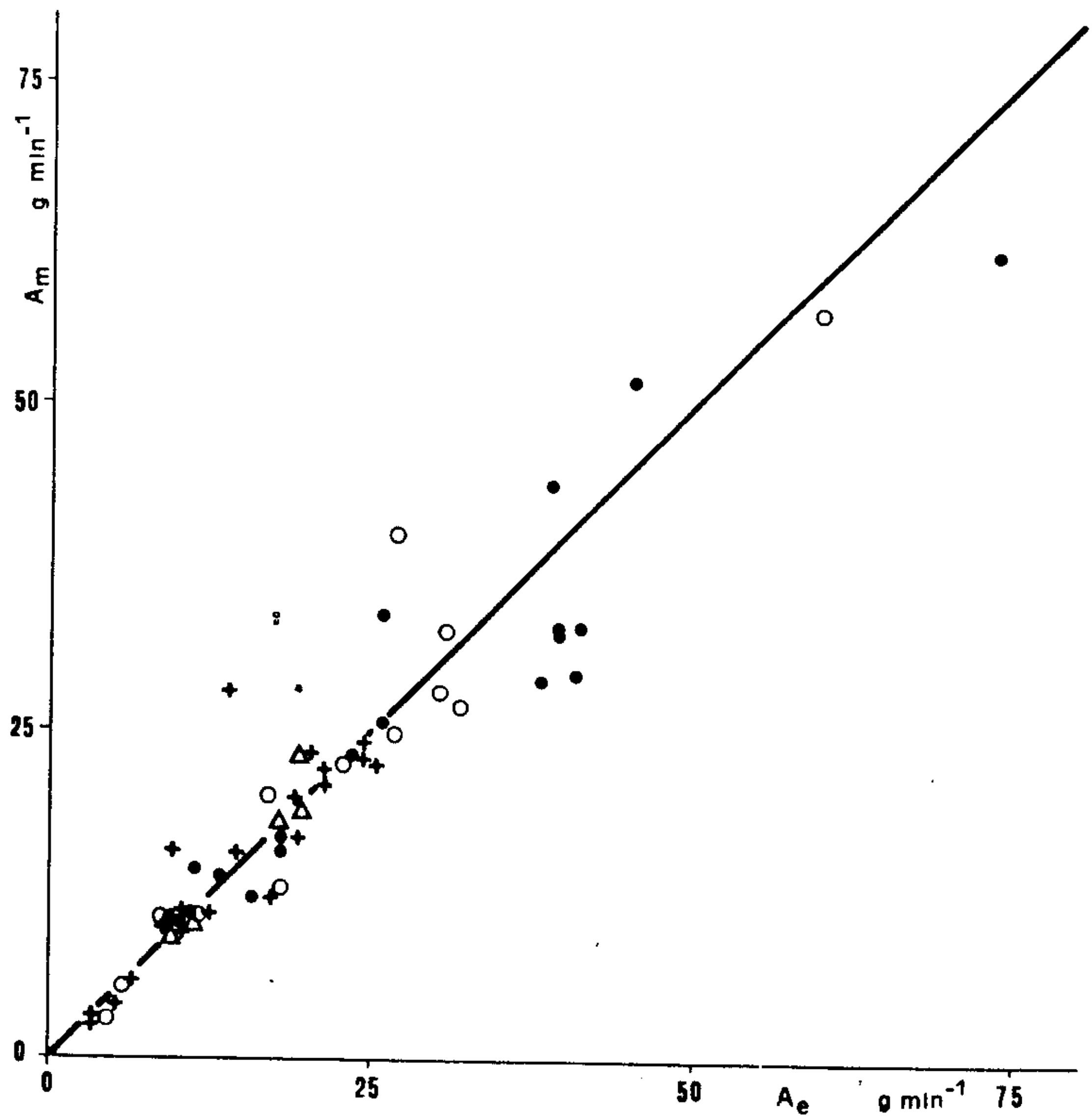

Fig 2: measured soil loss (A_m) versus estimated soil loss (A_e)