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Soil vulnerability in Uruguay: potential effects of an increase in erosive rainfall on soil loss

Carlos Víctora*, Aarón Kacevas, Héctor Fiori

Dirección de Suelos y Aguas, Dirección General de Recursos Naturales Renovables, Ministerio de Ganadería, Agricultura y Pesca, Avda. Garzón 456, Montevideo, Uruguay

ABSTRACT: Climate change is likely to modify rainfall patterns and their interaction with the soil. This paper addresses soil vulnerability in terms of soil loss resulting from increases in the amount of rainfall. Four agricultural soils from Uruguay were studied: 2 'Vertisol Rúptico' soils (Typic Pelluderts), 1 'Brunosol Subéutrico Típico' and 1 'Brunosol Subéutrico Lúvico' (Typic Argiudolls). A field rainfall simulator was used to produce rain events of controlled intensity. Three of the soils were exposed to a constant rain of 70 mm h^{-1}, which is the intensity of 30 min erosive rain events with a return period of 2 yr. The remaining soil, which is characterized by a high infiltration rate, was exposed to 140 mm h^{-1} rain. A 20 mm rainfall was applied on soil previously wet to saturation of the A horizon. The surface was prepared as bare soil seedbed on natural slopes (which are 2 to 5% steep, depending on the soil). The results obtained were corrected for a constant slope according to the Universal Soil Loss Equation (USLE). Soil losses (in kg ha^{-1}) for rainwater depths (amounts) of 5, 10, 15 and 20 mm respectively were: Vertisol (Serie Tala): 25, 136, 273 and 437; Vertisol (Serie Jesús María): 52, 291, 1233 and 2633; Brunosol (Serie Pando): 368, 961, 1725 and 2683; Brunosol (Serie Colonia Brause): 48, 60, 115 and 224. These results are indicative of: (1) a major difference in the degree of vulnerability among soils, and (2) an increase in the soil loss rate as a result of the increase in the amount of applied rainfall. The high sensitivity of the Uruguayan soils to climate-change-induced potential variations in rainfall pattern is thus confirmed.

KEY WORDS: Soil loss · Erosion · Erodibility · Rainfall · Typic Pelluderts · Argiudolls · Climate change · Soil vulnerability · Uruguay

1. INTRODUCTION

The rainfall pattern in Uruguay is likely to be affected by a change in climate. Different changes have been projected, depending on the climate model used, including incremental precipitation scenarios. Furthermore, a 200 mm increase in total annual precipitation between the late 19th century and the present has been observed through the analysis of precipitation time series for Montevideo. Similar behaviour was found for 8 weather stations in other parts of the country on the basis of shorter time series (1951 to 1991) (Bidegain & Deshayes 1992). These potential and actual increments in the frequency, duration or intensity of rainfall are likely to cause alterations of precipitation-soil interactions. This would result in variations in soil vulnerability, measured as kg of soil loss caused by rainfall erosion.

The vulnerability of various soils under climate change scenarios with positive precipitation increments—expressed in terms of water depth and related directly to the rainstorm duration—was estimated in this study using a physical simulation model (rainfall simulator). The data thus generated and recorded provide input for improving the performance of mathematical simulation models.

Results from the analysis of precipitation records at the national level (Rodríguez Fontal 1984) and estimates of actual erosive potential of local rain events—displayed on an iso-erodent line map (Rovira et al. 1982, Sorrondegui 1996)—are available. This information, together with the initial soil loss data measured under natural rainfall in standard runoff plots (García

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*E-mail: u31960@chasque.apc.org

et al. 1984), was used as input for models such as the Universal Soil Loss Equation (USLE) in order to estimate rainfall erosion in Uruguayan soils (e.g. Koolhas 1977, Puentes 1983).

Several studies on soil loss caused by erosive rain events, based either on natural rainfall or simulated rainfall data, are reported in the international literature. Rainfall simulators allow a large amount of data to be obtained within a short time period, almost independently from climatic conditions and at a lower cost per unit (Meyer 1988).

The evolution of the erosion rate was explained by Meyer & Harmon (1989), on the basis of laboratory studies on the effects of different rain intensities on the erosion process, by means of a power equation:

$$E = a \cdot I^b$$

where E is the erosion rate in Mg ha^{-1} h^{-1}; a and b are, respectively, the coefficient and the power term of the equation; and I is the rain intensity in mm h^{-1}. Different results were found, depending on the soil, the slope steepness and slope length.

Further, Meyer & Harmon (1992a), who estimated the erosion resulting from the application of several rainstorms, observed that the erosion rate (in Mg ha^{-1} h^{-1}) increased following an increase in the accumulated rainfall of up to 50 mm, and then decreased. Different results were found for different soils, and in some cases for different times of the year (fall or spring). A laboratory assessment of the effects of slope shape, rain energy and rain intensity on the soil loss rate was carried out by the same authors (1992b). A variation in the relation between rain intensity and erosion rate following changes in rain energy was found. The relation between rain intensity and soil loss was also described in this case by means of a power equation.

Keren (1991) observed that the soil loss rate increased with accumulated rainfall until the latter reached 50 mm, and then remained constant. Similar results were found as well by Giménez et al. (1992), who observed that the sediment production rate would increase for a certain period and would then start to decrease.

Flanagan et al. (1988) studied the effects of several rainstorms on soil loss, runoff and infiltration. The results obtained for soils that had been wet by previous rain events significantly differed from those for the initially dry soils. They also observed differences in runoff and infiltration according to the distribution in time of the peaks of intensity of the simulated rainstorms.

McIsaac & Mitchell (1992) analyzed the variation in time of soil loss for maize and soybean crops. These authors stated that a 1 yr experiment was not sufficient to assess erosion, since the erosion process is very erratic and varies as a result of the preceding rainfall conditions (and therefore soil moisture) and of plant coverage. No statistically significant differences were found when comparing the results of their experiment with the measured values for an 8 yr period under natural rainfall conditions. Alberts et al. (1987) also emphasized the convenience of repeating simulated events over several years in order to account for the effects of soil moisture and previous rainfall on soil loss estimates.

Proffit et al. (1991) compared 2 different soils, a Vertisol and an Aridisol, finding considerably higher losses in the case of the latter under various rain intensity and rain duration conditions.

Bajracharya et al. (1992) encountered soil loss differences among several soils under a constant-intensity rain (70 mm h^{-1}). Those differences were considered to be related to the physical characteristics of each soil and to the initial moisture conditions.

The study described herein consisted of a vulnerability assessment of Uruguayan soils to a potential increase in rainfall related to climate change, measured in terms of soil loss. It was part of a research program carried out within the framework of a technical cooperation agreement between the Dirección de Suelos y Aguas of the Dirección General de Recursos Naturales Renovables-Ministerio de Ganadería Agricultura y Pesca and the Programa de Manejo de Recursos Naturales y Desarrollo del Riego (PRENADER).

2. METHODOLOGY

2.1. Selected soils

Two 'Vertisol Rúptico' soils (Typic Pelluderts), one 'Brunosol Subéutrico Típico' and one 'Brunosol Subéutrico Lúvico' (Typic Argiudolls) were selected for the study. These soils are representative of the intensive agriculture region of the country (Dirección de Suelos 1982).

One of the Vertisols (Serie Tala) and one of the Brunosols (Serie Pando) developed on Quaternary unconsolidated sedimentary rock (silty clay textured soils of the 'Libertad' Formation). The other 2 soils (Vertisol Serie Jesús María, Brunosol Serie Colonia Brause) developed on sedimentary rock of variable lithology, with a predominance of sandy layers ('Raigón' Formation, of Tertiary origin).

All selected soils are deep, differing mainly in the texture and structure of the upper horizons: Vertisol (Typic Pelludert) is a clayey, well-structured soil, while Brunosol (Argiudoll) has a well-developed B horizon with accumulation of clay.

2.2. Experimental plots and the rain simulator

The sites for the experiments were selected on the basis of both the presence of soils representative of the soil unit under study and logistic criteria (e.g. ease of access and proximity to a source of water). Two 3.4 × 1.0 m experimental plots (termed A and B) were established on a homogeneous slope at each site. The surface was manually tilled as a seedbed. Runoff was measured at predetermined volumetric intervals, with a higher frequency at the beginning (1, 2, 3, 4, 6, 8, 12, 16 l, etc.). The time at which the measurements were taken was recorded. An aliquot of the simulated rain was collected in a central container in order to measure, and if necessary adjust, its intensity throughout the experiment. In the case of the Vertisol Jesús María an experimental plot was set up on both the shallow and the deep phases (profiles) of this soil in order to quantify the losses for each one.

The rainfall simulator used was composed of an iron structure holding an oscillating pipe, which carried a pressure gauge and 3 Vee-Jet 80/100 nozzles working at 0.3 kg cm^{-2} pressure and at 2.4 m height. A rain with characteristics similar to those of the natural rain of temperate zones as regards, for example, drop size, terminal velocity and kinetic energy was thus generated (Meyer & McCune 1958). The desired intensity (70 mm h^{-1}) was obtained by intermittent rain application. The field equipment also included a mobile 1500 l tank, an electric generator, a water pump and a windshield.

Incremental precipitation change scenarios were generated. For that purpose, 45- and 20-min rains were applied in order to produce a uniform initial soil moisture and saturation of the surface A horizon. A 20-min rain event was applied 15 min after the prewetting was over; measurements were taken under 5, 10, 15, and 20 mm rainfall conditions.

The selection of rain intensity (70 mm h^{-1}) and duration (20 min) was based on the characteristics and return periods of rain events in the country, as well as on national and international work on the topic. The rain applied in this case has a return period of about 2 yr (Rovira et al. 1982, Rodríguez Fontal 1984) (Table 1). A rain with an intensity of 140 mm h^{-1} was applied to one of the soils (Brunosol Serie Colonia Brause) which, due to its high infiltration rate, required a rain intensity over 70 mm h^{-1} in order to generate runoff.

2.3. Soil loss determination

The sediment concentration in the runoff samples was measured in the laboratory using the gravimetric method.

Table 1. Rainwater depth (mm) and rain intensity (mm h^{-1}) for different return periods and rain event durations (confidence level = 90%). Source: Rodríguez Fontal (1984)

Return period (yr)		Duration of rain event (min): 5	10	20	30	60
2	Depth	15.9	22.1	30.8	37.3	52.0
2	Intensity	191	133	92	75	52
3	Depth	16.9	23.5	32.7	39.7	55.3
3	Intensity	203	141	98	79	55

Soil loss during the period between samples was estimated on the basis of the sediment concentration in the sample corresponding to that period. The total soil loss for each event, expressed in kg ha^{-1}, is the sum of the losses for each period.

2.4. Statistical procedure

Soil loss estimate for different rainwater depths (5, 10, 15 and 20 mm) was performed independently for each plot using regression models. All models used provided significant adjustments. Model selection was based on determination coefficients and visual assessment in those cases when more than one model fitted.

Since all soils and plots behaved differently, it was necessary to have a model adjusted for each specific case. In some cases it was even necessary to apply more than one equation for the assessment of soil loss under different rainfall conditions. Upon estimation of soil losses for 5, 10, 15 and 20 mm of rainfall, a curve was fitted to represent the accumulated loss and loss rate trends for the different soils as a function of rainfall.

3. RESULTS

Estimated loss for each soil under 5, 10, 15 and 20 mm of rainfall respectively was (in kg ha^{-1}): Vertisol Tala: 25, 136, 273 and 437; Vertisol Jesús María: 52, 291, 1233 and 2633; Brunosol Pando: 368, 961, 1725 and 2683; Brunosol Colonia Brause: 48, 60, 116 and 224 (Table 2).

The increase in accumulated soil loss was, in all cases, proportionally higher than the increase in rainwater depth.

The relation between the accumulated soil loss and the amount of rain applied was, in the case of 3 soils, represented by power equations. An exponential equation provided the best fit in the case of the Brunosol Colonia Brause (Figs. 1 & 2).

Table 2. Soil loss estimates (kg ha^{-1}) for each soil unit under different rainwater depths. CV: coefficent of variation

Depth (mm)	Soil loss Plot A	Soil loss Plot B	Average	SD	CV (%)
Vertisol Tala					
5	32.74	17.62	25.18	10.69	42.46
10	104.65	166.96	135.81	44.06	32.44
15	206.50	339.82	273.16	94.27	34.51
20	334.48	539.72	437.10	145.13	33.20
Vertisol Jesús María					
5	58.88	44.61	51.75	10.09	19.50
10	114.57	467.00	290.79	249.21	85.70
15	169.12	2296.84	1232.98	1504.53	122.02
20	222.93	5042.50	2632.72	3407.95	129.45
Brunosol Pando					
5	479.36	255.85	367.61	158.05	42.99
10	1240.53	680.60	960.57	395.93	41.22
15	2050.09	1400.35	1725.22	459.44	26.63
20	2928.97	2437.60	2683.29	347.45	12.95
Brunosol Colonia Brause					
5	0.00	96.64	48.32	68.33	141.42
10	0.00	120.65	60.33	85.31	141.42
15	76.33	155.47	115.90	55.96	48.28
20	248.14	200.32	224.23	33.81	15.08

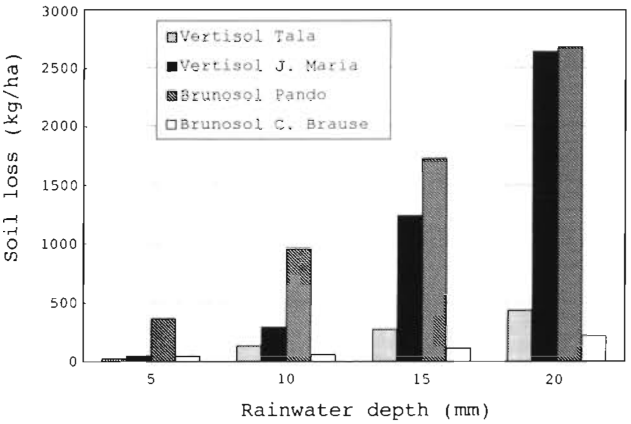

Fig. 1. Accumulated soil loss as a function of rainwater depth

Relatively low soil losses and the lowest rates of increase in soil loss in relation to successive increments in rainwater depth were observed for Vertisol Tala and Brunosol Colonia Brause. Soil losses and soil loss rate were considerably higher for Brunosol Pando and Vertisol Jesús María (Fig. 3).

Even though lower values of the coefficient of variation would be desirable—particularly so in some of the cases—the spatial variability of the soils must also be taken into account. This is especially the case for Vertisol Jesús María, as discussed below.

Soil loss rates (kg ha^{-1} of soil loss for each rainwater depth interval) are presented in Table 3.

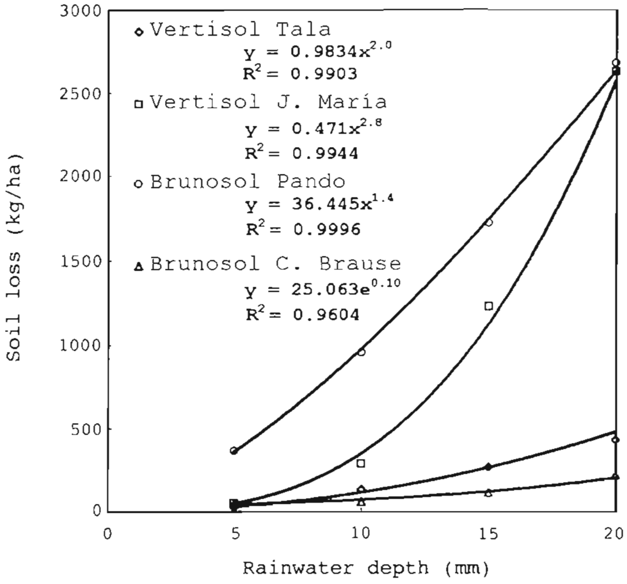

Fig. 2. Accumulated soil loss curves

The soil loss rate was also represented by a power equation in the case of 3 of the soils. Values for the Brunosol Colonia Brause were best represented by an exponential equation (Fig. 3).

The relative soil losses for the different rainwater depths analyzed are shown in Table 4. A comparison of these values among soils in percentage terms is shown in Table 5.

4. DISCUSSION

The observed evolution of soil loss rate is consistent with findings from other studies reported in the literature which describe a rate of increase in soil loss proportionally higher than the increase in rainwater depth (Meyer & Harmon 1989, 1992b, Keren 1991, Giménez et al. 1992). Both soil loss rates and accumulated soil losses were represented by power equations in the case of 3 of the 4 soils under study.

One of the soils, Brunosol Colonia Brause, behaved differently than expected, both with regard to soil loss rate and to accumulated soil loss. A slight decrease in loss was observed during the first stages of the experiment. The low values obtained for 5 and 10 mm of applied rainfall at both plots, which could not be explained, are likely to have been caused by some experimental failure. However, towards the end of the experiment both plots had similar values, reflecting the expected trend.

It was observed that different soils behaved considerably differently under the simulated rainfall conditions, which is consistent with results from previous

Table 3. Soil loss rate (kg ha^{-1} mm^{-1}) for different rainwater depth intervals

Depth (mm)	Vertisol Tala	Vertisol Jesús Maria	Brunosol Pando	Brunosol Colonia Brause
5	5	10	74	10
10	22	48	119	2
15	27	188	153	11
20	33	280	192	22

Table 4. Relative soil losses for the different rainwater depths (soil loss at 5 mm of rainfall = 1)

Depth (mm)	Vertisol Tala	Vertisol Jesús Maria	Brunosol Pando	Brunosol Colonia Brause
5	1	1	1	1
10	5.4	5.6	2.6	1.3
15	10.9	23.7	4.7	2.4
20	17.5	50.6	7.3	4.7

Table 5. Comparison of soil loss for different rainwater depths (soil loss in Brunosol Pando at 20 mm depth: 2632.7 kg ha^{-1} = 100)

Depth (mm)	Vertisol Tala	Vertisol Jesús Maria	Brunosol Pando	Brunosol Colonia Brause
5	1	2	14	2
10	5	10	36	2
15	10	46	64	4
20	16	98	100	8

studies (e.g. Bajracharya et al. 1992, Meyer & Harmon 1992a). The differences encountered were due to the morphological and physico-chemical characteristics of the soils, which determine the resistance to detachment by raindrop impact, the infiltration rate, the surface sealing susceptibility, etc.

Brunosol Pando and Vertisol Jesús María proved to be the most erodible soils. Brunosol Pando has a silty texture (silty clay), a well-developed textural B horizon at a shallow depth, and a moderately structured surface horizon. The high erodibility of this soil results from the combination of these factors.

Although lower losses than observed could have been expected with regard to Vertisol Jesús María given the characteristics of the soil Order (Vertisols), it actually displayed one of the highest erosion values among the soils under study. This soil has a more lightly textured surface horizon and is less well structured than the Vertisols in general. Additionally it has 2 well-defined phases (profiles), a deep one and a shallow one, which are found close to each other and comprise a single soil complex. During this study an experimental plot was located on each one of the phases of this double-profile soil in order to better assess the erosion process of the whole soil. Marked soil loss and rate differences were encountered between both plots as a result of the defined characteristics of each profile (e.g. depth, structure and texture). A considerable sideslope internal water movement from the shallow towards the deep profile, resulting from the topography of the subsurface lower horizons (particularly the C horizon), could explain the higher surface runoff volumes, and consequently the higher soil losses, recorded on the deep profile plot (plot B) (Table 2).

On the other hand, the Brunosol Colonia Brause has a sandy texture—the lightest among the soils under study—which is responsible for the high infiltration rate and hydraulic conductances, the low runoff, and consequently the lower erodibility of this soil. A 140 mm h^{-1} rain had to be applied on this soil in order to induce runoff.

Low soil losses were also recorded for Vertisol Tala as a result of its being a well-structured soil, thus enhancing resistance to factors such as raindrop impact. The differences in the 2 profiles of this Vertisol are less marked, since the shallow profile is deeper than in the previous case and the soil surface is more homogeneous as a result of agricultural use. Therefore,

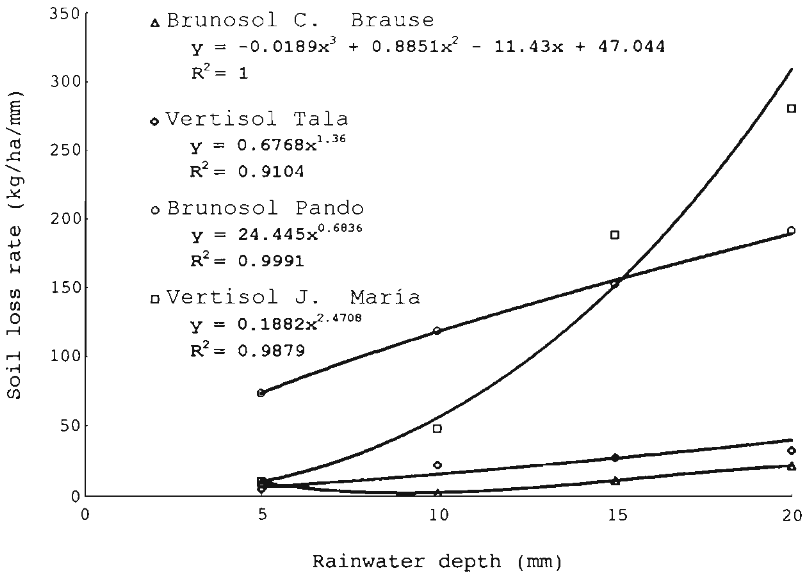

Fig. 3. Evolution of soil loss rate as a function of rainwater depth

the difference between values obtained for experimental plots on the deep and shallow profiles was less significant.

The above results are indicative of the degree of vulnerability of each soil, described in terms of its erodibility, under climate change scenarios with precipitation increases defined by the duration of the rainstorm and resulting in an increase in the rainwater depth.

5. CONCLUSIONS

Considerable differences in vulnerability to climate change, described in terms of soil loss response under incremental precipitation scenarios, were found among the 4 soils under study. Such differences were observed with respect to (1) the evolution of soil loss rates (measured in kg ha^{-1} mm^{-1} of rainfall) and (2) accumulated soil loss (measured in kg ha^{-1}).

Vulnerability in terms of soil erodibility was not closely related to the soil taxonomic group. However, in all cases it was found that soil losses increased at a higher rate than rainfall. This fact indicates that, unless corrective management measures are adopted, a climate change in this direction would enhance loss of the upper soil layers, which—apart from being of high agricultural and economic importance—could hardly be recovered.

The factors involved in precipitation-soil interactions and in soil responses to climate change are extremely complex and their behaviour is difficult to predict. Therefore, additional studies of this issue under local conditions are required in order to produce physical simulations of the vulnerability of the different soils in the country. The information presented above, which resulted from physical simulations for a specific climate change feature, may provide an input for mathematical simulations and thus contribute to broader assessments of climate change effects.

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