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Water erosion risk assessment and impact on productivity of a Venezuelan soil

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Abstract

Soil losses affect the physical, chemical and biological soil properties and as a consequence reduce soil productivity. Erosion reduces or eliminates root-explorable soil depth and crop available water, selectively decreases the nutrient and organic matter content, and exposes soil layers with unsuitable characteristics for crop growth. Yield is hence assumed to be a function of root growth, which in turn is a function of the soil environment. In order to evaluate the water erosion impact on soil properties and productivity, a study was carried out on a Typic Haplustalfs soil, with sorghum (*Sorghum bicolor* (L) Moench), located in Chaguaramas in the Central Plains of Venezuela. Four different study locations with the same soil type, with slopes ranging from 3% to 6% and with different levels of erosion were selected: Chaguaramas I (slightly eroded), Chaguaramas II, (moderately eroded), Chaguaramas III (moderately eroded), and Chaguaramas IV (severely eroded). A sorghum–livestock farming system was introduced 30 years ago. Secondary tillage with a disc harrow (without mulch on the topsoil) was applied for seedbed preparation. Fertilizers and pesticides were applied uniformly over the entire fields. Soil samples from each horizon were analysed for particle size distribution, water retention, bulk density, pH and organic matter content. The relative production potential was estimated using the Productivity Index developed by Pierce et al. [Pierce, F.C., W.E. Larson, R.H. Dowdy and W.A. Graham. 1983. Productivity of soils: assessing long-term changes due to erosion. Journal of Soil and Water Conservation. 38 39–44.], and adapted to the methodology proposed by Delgado [Delgado F. 2003. Soil physical properties on Venezuelan steeplands: applications to conservation planning. The Abdus Salam International Centre for Theoretical Physics. College on Soil Physics. 11 pp.]

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for Venezuelan soil conditions. The Productivity Index (PI) could estimate the tolerable rate of soil productivity loss. A soil erosion risk was assessed by the Erosion Risk Index (ERI) taking into account the soil hydrological characteristics (infiltration–runoff ratio), rainfall aggressiveness and topography (slope). The Productivity Index (PI) and the Erosion Risk Index (ERI) were used to classify the lands for soil conservation priorities, for conservation requirements and for alternative land uses. The results showed that: (a) the Productivity Index (PI) decreased with increasing level of erosion, (b) the Productivity Index (PI) was mainly affected by changes in available water storage capacity, bulk density and pH, (c) the erosion risk (ERI) was strongly affected by slope gradient and rainfall aggressiveness, (d) the areas were classified as critical lands and super-critical lands, with high to very high soil conservation requirements, depending on the level of soil erosion.

Keywords: Erosion Risk Index; Soil Productivity Index; Sorghum; Typic Haplustalfs; Infiltration; Runoff; Venezuela

1. Introduction

Soil losses by erosion affect the physical, chemical and biological soil properties and as a consequence reduce soil productivity being the capacity of a soil, in its normal environment, to produce a particular plant or sequence of plants under a specified management system (Soil Sci. Soc. Amer., 1975).

Erosion reduces or eliminates root-explorable soil depth and crop available water, selectively decreases the nutrient and organic matter content, and exposes soil layers with unsuitable characteristics for crop growth.

Yield is hence assumed to be a function of root growth, which in turn is a function of the soil environment. The decline in yield with the reduction in topsoil depth can be related to the A horizon thickness. But erosion can reduce productivity so slowly that the reduction may not be recognized until it is no longer economically suitable for growing crops.

The Productivity Index (PI) model has served as a useful tool for estimating the relative productive potential of different soils, long-term erosion-productivity impacts, and permissible soil losses for conservation planning (El-Swaify and Fownes, 1989).

The objective of our work was to evaluate the water erosion impact on soil productivity, using the Soil Productivity Index (PI) developed by Pierce et al. (1983) and adapted by Delgado (2003) for Venezuelan soil conditions.

2. Materials and methods

The study was carried out on a Typic Haplustalf soil located in Chaguaramas in the Central Plains of Venezuela with Sorghum (*Sorghum bicolor* (L) Moench) as the crop.

Four different study locations with the same soil type, with slopes ranging from 3% to 6% and with different levels of erosion were selected: Chaguaramas I (slightly eroded: no loss of topsoil), Chaguaramas II, (moderately eroded: 5 cm loss of topsoil), Chaguaramas III (moderately eroded: 8 cm loss of topsoil), and Chaguaramas IV (severely eroded: 10 cm loss of topsoil).

The production system was a sorghum–livestock farming system introduced 30 years ago. Secondary tillage with a disc harrow (without mulch on the topsoil) was applied for seedbed preparation. Fertilizers and pesticides were applied uniformly over the entire fields.

Soil samples from each horizon were analyzed for particle size distribution, water retention, bulk density, pH and organic matter content.

Delgado (2003) proposed the Productivity Index (PI) as a function of the most relevant factors for Venezuelan soil conditions:

$$PI = \sum_{i=1}^{n} (A_i \cdot B_i \cdot C_i \cdot K_i) \quad (1)$$

where A_i to K_i are factors which have following meaning:

Factor **A**, conditions that regulate the *air–water relations* of horizon i:

- In dry climate (P/ETP<0.50): Factor **A**=sub-factor A_1 (soil available water storage capacity)
- In humid climate (P/ETP>2.00): Factor **A**=sub-factor A_2 (soil aeration capacity)
- In sub-humid to dry climate (0.50≤P/ETP≤2.00): Factor **A**=most limiting value (the lowest numerical value) between sub-factors A_1 and A_2

Factor **B**, conditions that determine *mechanical resistances* (impedances) to the crop root exploration in horizon i:

- If the volumetric content of coarse fragments in the soil is less than or equal to 30%, then Factor **B**=sub-factor B_1 (soil compaction)
- If the volumetric content of coarse fragments in the soil is greater than 30%, then Factor **B**=sub-factor B_2 (coarse fragments)

Factor **C**, conditions that regulate the *potential fertility* of horizon i:

- In humid climate (P/ETP>2.00): Factor **C**=sub-factor C_1 (soil reaction)
- In dry climate (P/ETP<0.50): Factor **C**=sub-factor C_2 (soil organic matter content)
- In sub-humid to dry climate (0.50≤P/ETP≤2.00): Factor **C**=most limiting value (lowest numerical value) between factors C_1 and C_2

Factor **K**, evaluates the relative importance of horizon i in the soil profile.

Each factor of the Productivity Index (PI) was evaluated in terms of the respective most relevant sub-factors, taking into consideration the local climate conditions. In our case the sub-factors were selected as follows: for A, the % clay and weak soil structure degree were selected as the most limiting sub-factor A_2 (see Fig. 1 in which A_2 is a function of the clay %); for B, the bulk density as a function of soil texture was selected, as sub-factor B_1 (see

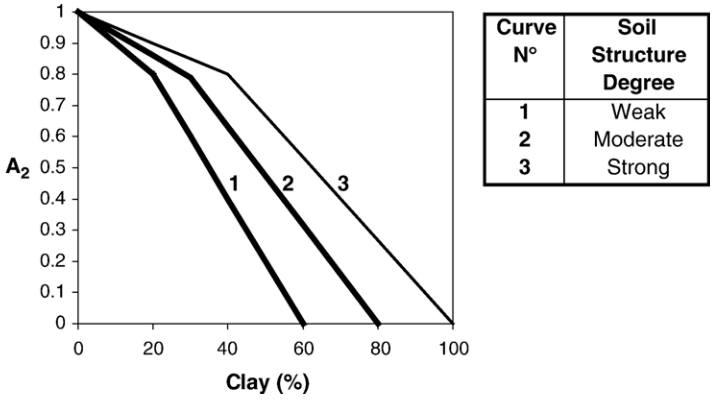


Fig. 1. Sub-factor A_2. Soil aeration capacity.

Fig. 2 in which B_1 is a function of bulk density) because the volume of coarse fragments in the soil is less than 30%; for C, the pH was selected as the most limiting sub-factor C_1 (see Fig. 3 in which C_1 is a function of pH); and K was calculated as $K_i = K_{cum}(i) - K_{cum}(i-1)$ as in Fig. 4 (in which K is a function of soil depth). In our case, we could therefore write Eq. (1) as:

$$PI = \sum_{i=1}^{n} (A_2 \cdot B_1 \cdot C_1 \cdot K_i) \tag{2}$$

The Productivity Index (PI) could estimate the tolerable rate of soil productivity loss using the approach to evaluate Soil Loss Tolerance, $T = \delta - H$, proposed by Delgado and Lopez (1998), where δ is permissible soil productivity loss (%), and H = sustainable land use for maintaining productivity in horizon (years). The values δ and H are assumed as

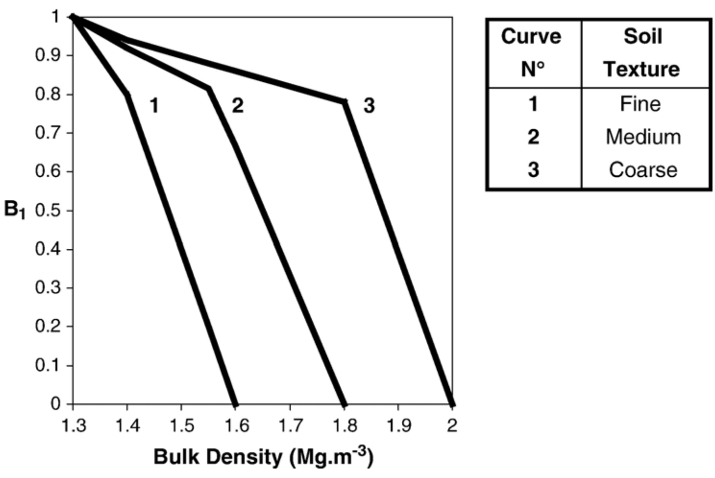


Fig. 2. Sub-factor B_1. Soil Compaction.

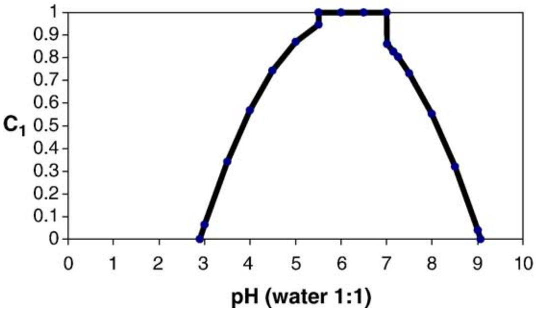


Fig. 3. Sub-factor C_1. Soil reaction (pH).

related to the needs and socio-economics premises adopted by the planners and soil conservationists. Normally, δ varies between 0.05 and 0.10 (5% to 10%), and H could be assumed to be 100 to 200 years.

To assess the value of δ, the following equation was applied:

$$\mathrm{PI_f} = \mathrm{PI_i}(1 - \delta) \tag{3}$$

where $\mathrm{PI_f}$ is the final soil productivity index, after soil removal, and $\mathrm{PI_i}$ is the soil initial productivity index.

A soil erosion risk was assessed by the Erosion Risk Index (ERI) taking into account the soil hydrological characteristics (infiltration/runoff ratio), rainfall aggressiveness and topography (slope). The Erosion Risk Index (ERI) was calculated by the following equation:

$$ERI = \frac{\eta}{10(1 - \alpha)} \tag{4}$$

where α evaluates the soil runoff potential in function of soil structure, soil particle sizes, and coarse fragments (Fig. 5), and η evaluates the impact of the terrain slope (modal slope)

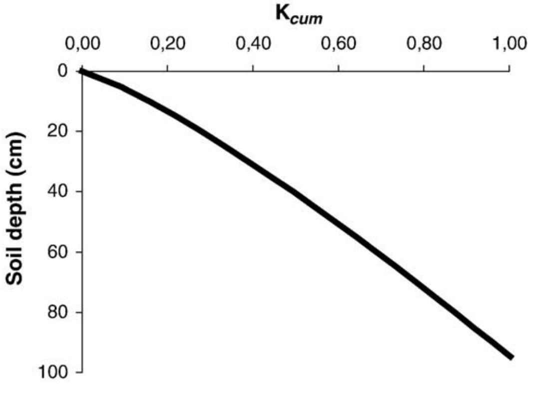


Fig. 4. Factor K of the soil productivity index (weighting factor).

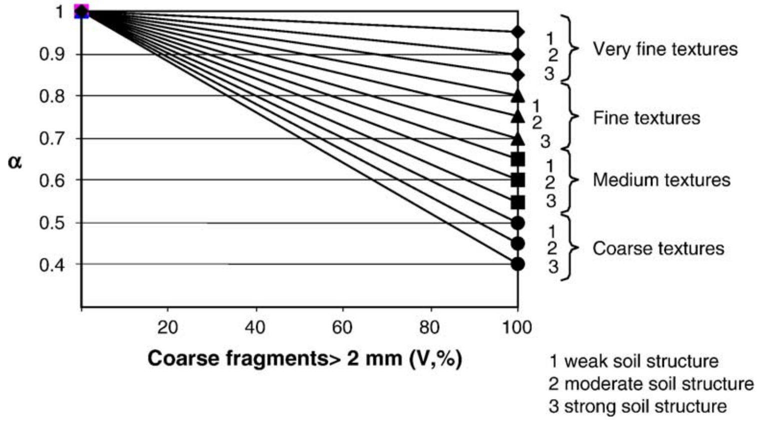


Fig. 5. Factor α of the erosion risk index.

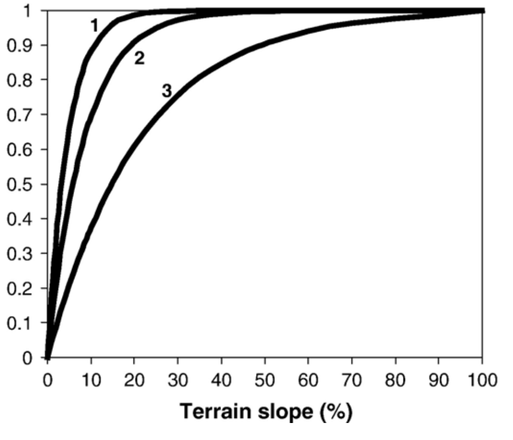
on erosion risk under different rainfall aggressiveness determined by the Fournier Index (Fournier, 1960, quoted by FAO-PNUMA, 1980):

$$F = p_{\mathrm{m}}^2/P \tag{5}$$

where F is the Fournier Index, p_{m} is the maximum monthly precipitation (mm), and P is annual precipitation (mm) (Fig. 6).

The Erosion Risk Index (ERI) has a value between 0 and 1, with 1 corresponding to a land unit that presents the highest potential conditions for inducing water erosion processes.

The Productivity Index (PI) and the Erosion Risk Index (ERI) were used to classify the lands for soil conservation priorities, for conservation requirements and for alternative land uses. They are assessed using a system similar to those developed by Sheng (1972) and Larson et al. (1988).



Curve N°	Fournier Index
1	> 30
2	15 – 30
3	< 15

Fig. 6. Factor η of the erosion risk index.

Table 1
Ranking the Soil Productivity Index (PI) and the Erosion Risk Index (ERI)

PI or ERI	Soil productivity or Erosion risk
≤0.10	Low
0.11–0.30	Moderate
0.31–0.50	High
>0.50	Very high

Relative values of soil productivity, estimated with the soil productivity index PI and relative values for the water erosion risk of a land unit, estimated by means of the Erosion Risk Index ERI, can be classified as indicated in Table 1.

3. Results

Table 2 shows the soil properties of the Venezuelan soils with different levels of soil erosion used to assess the Productivity Index (PI). Those properties are the result of different erosion levels caused by different number of years under a sorghum–livestock farming system. The results indicate that the PI is highest in the lightly eroded soil (PI = 0.55), whereas the severely eroded soil shows the lowest PI value (PI = 0.27). PI was mainly affected by changes in available water storage capacity (subfactor A as a function of clay %), bulk density (subfactor B) and pH (subfactor C).

Table 2
Soil properties and Soil Productivity Index (PI)

Erosion level	Depth (cm)	Clay (%)	Sub-factor A	Bulk density (mg m^{-3})	Sub-factor B	pH	Sub-factor C	Sub-factor K	PI
I	0–20	12.0	0.95	1.55	0.85	5.9	1.00	0.30	0.24
	20–38	17.0	0.90	1.63	0.60	6.2	1.00	0.18	0.10
	38–70	25.0	0.85	1.60	0.82	6.0	1.00	0.30	0.21
								Very high	0.55
II	0–15	12.0	0.95	1.62	0.80	5.4	0.95	0.23	0.17
	15–35	19.5	0.85	1.68	0.50	5.9	1.00	0.22	0.09
	35–60	27.0	0.82	1.61	0.82	5.7	1.00	0.35	0.24
								High	0.50
III	0–12	14.0	0.95	1.57	0.85	5.4	0.95	0.18	0.15
	12–32	20.5	0.85	1.70	0.45	5.0	0.85	0.22	0.08
	32–42	23.0	0.82	1.70	0.45	4.2	0.60	0.10	0.04
	42–70	37.0	0.75	1.60	0.82	4.8	0.80	0.30	0.18
								High	0.37
IV	0–10	10.0	0.9	1.58	0.82	5.3	0.90	0.15	0.09
	10–18	14.0	0.87	1.63	0.64	5.1	0.88	0.10	0.05
	18–35	17.0	0.85	1.63	0.64	5.2	0.92	0.20	0.10
	35–45	24.0	0.75	1.75	0.20	5.8	1.00	0.10	0.015
	45–70	20.0	0.80	1.83	0.10	5.0	0.85	0.25	0.017
								Moderate	0.27

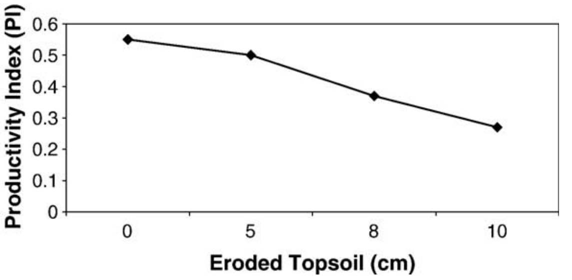


Fig. 7. Soil erosion vulnerability.

Soil erosion vulnerability is the rate of changes in productivity, measured by changes in PI values per unit of removed soil by erosion. Fig. 7 shows a strong relationship between depth of removed topsoil and PI.

The factor α of the Erosion Risk Index (ERI) was estimated taking into account the granulometry (texture and % coarse fragments) and soil structure degrees of topsoil. The factor η of the Erosion Risk Index (ERI) was estimated taking into account the interaction between terrain slope (modal slope %) and Fournier Index. Both factors are shown in Table 3. The erosion risk was strongly influenced by slope gradient and especially by rainfall aggressiveness (Fournier Index).

Finally, the Soil Productivity Index (PI) and the Erosion Risk Index (ERI) enabled to establish a land classification for soil conservation using the system proposed by Delgado

Table 3
Erosion risk

Soil	Texture	Coarse fragments (%)	Soil Structure degree	Factor α	Factor η	Modal Slope gradient	Fournier Index	Erosion Risk Index (ERI)	Erosion Risk
I	Sandy loam	14.0	Weak	0.93	0.69	4.7	36.86	0.98	Very high
II	Sandy loam	15.5	Weak	0.90	0.70	4.5	36.86	0.77	Very high
III	Sandy loam	14.2	Weak	0.92	0.69	4.8	36.86	0.86	Very high
IV	Sandy loam	15.0	Weak	0.91	0.69	4.8	36.86	0.76	Very high

Table 4
Land classification system for soil conservation on tropical steeplands

		Erosion Risk Index (ERI)				General land use
		≤0.10 (low)	0.11–0.30 (moderate)	0.31–0.50 (high)	>0.50 (very high)	
Soil Productivity Index (PI)	≤0.10 (low) 0.11–0.30 (moderate)	Reserve lands (R) (4th priority conservation treatment)		Critical lands (C) (2nd priority conservation treatment)		Permanent vegetation Agroforestry Special crops/agroforestry
	0.31–0.50 (high) >0.50 (very high)	Sub-critical lands (S) (3rd priority conservation treatment)		Super-critical lands (P) (1st priority conservation treatment)		Semi-intensive agriculture Intensive agriculture

Table 5
Land classification for soil conservation

Soil	Productivity Index (PI)	Erosion Risk Index (ERI)	Soil conservation requirements	Land Classification	General Land Use
I	0.56	0.98	Very high	Super-critical land (P) (1st priority conservation treatment)	Intensive agriculture
II	0.50	0.77	Very high	Super-critical land (S) (1st priority conservation treatment)	Semi intensive agriculture
III	0.37	0.86	Very high	Super-critical land (P) (1st priority conservation treatment)	Semi intensive agriculture
IV	0.27	0.76	Very high	Critical land (C) (2nd priority conservation treatment)	Special crops/agroforestry

(2003) (Table 4). The areas were classified as critical lands and super-critical lands, with very high soil conservation requirements, depending on the level of soil erosion (Table 5).

Although originally the different areas were classified as slightly eroded (area I), moderately eroded (area I and II) and severely eroded (area IV), their erosion risk index was very high for the four areas. However, their productivity index was very high for area I, high for area II and III and moderately high for area IV.

4. Conclusions

Erosion reduced the soil productivity by affecting the soil properties and soil depth. The presence of a subsurface horizon that had physical and chemical properties contrasting sharply with the overlaying surface soils had a strong influence on topsoil depth–productivity index relationships.

The Soil Productivity Index (PI) can be used as a criterion of tolerance of soil loss due to soil erosion. Soil Productivity and Erosion Risk Indices (ERI) allowed classifying general land use areas in view of soil conservation systems.

In the Central Plains of Venezuela, on slightly eroded soil, intensive agriculture is possible, whereas on severely eroded soil only special crops or agroforestry can be applied. Moderately eroded soil can be used with semi-intensive agriculture.

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