Soil Physical Properties on Venezuelan Steeplands: Applications to Soil Conservation Planning

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Abstract

This paper presents a framework to support decision making for soil conservation on Venezuelan steeplands. The general approach is based on the evaluation of two important land qualities: soil productivity and soil erosion risk, both closely related to soil physical properties. Soil productivity can be estimated from soil characteristics such as soil air-water relationships, soil impedances and soil fertility. On the other hand, soil erosion risk depends basically on soil hydrologic properties, rainfall aggressiveness and terrain slope. Two indexes are obtained from soil and land characteristics: soil productivity index (PI) and erosion risk index (ERI), each one evaluates the respective land quality. Subsequently, a matrix with these two qualities shows different land classes as well as soil conservation priorities, conservation requirements and proposed land uses. The paper shows also some applications of the soil productivity index as an approach to evaluate soil loss tolerance for soil conservation programs on tropical steeplands.

INTRODUCTION

Agriculture on Venezuelan Andes is affected by two very important biophysical land qualities: soil productivity and soil erosion risk. The notorious scarcity of complex data in these tropical mountains hinders conservation planning for land use.
Thus, the need to count on analytical tools that permit estimating soil productivity in terms of easily obtainable soil variables, or simple methods that permit forecasting the water erosion risk on steeplands with scarce data.

In this sense and in order to direct sustainable agriculture on Venezuelan steeplands, a methodological approach for soil conservation planning has been developed at CIDIAT, University of Los Andes, Mérida-Venezuela, over the last decade. This approach is sustained mainly on the evaluation of soil physical properties related to these two important land qualities: soil productivity and soil erosion risk.

SOIL PRODUCTIVITY

As a central concept, soil productivity is the capacity of a soil, in its normal environment, to support plant growth under a specific management system. In this sense, soil productivity is a function of the soil's physical, chemical and biological properties as well as climate, management and other non-inherent factors used to produce crops. Crop yields are usually used as a measure of soil productivity.

To quantify soil productivity on Venezuelan steeplands, during the last decade we have been modifing and validating a numerical approach (Soil Productivity Index) initially developed by Pierce *et al*., (1983).

The Productivity Index (PI) model is a derived measure of soil productivity. The PI model is an algorithm based on the assumption that crop yield is a function of root development, which in turn is controlled by the soil environment.

The Productivity Index is calculated with the following multi-factorial model:

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

where PI is the Soil Productivity Index ranging from 0 to 1. Value 1 corresponds to a soil without any kind of limitation for root development.

In the present approach factor A_i evaluates conditions that regulate the air-water relations of horizon *i;* factor B_i evaluates the conditions that determine mechanical resistances (impedances) to the crop root exploration in horizon *i; and* factor C_i evaluates the conditions that regulate the potential fertility of horizon *i*. Finally, K_i evaluates the relative importance of horizon *i* in the soil profile (weighting factor of the respective horizon) and also the importance of soil depth. All these factors are evaluated in each soil horizon n, up to a depth of 100 cm if the soil has a depth equal to or greater than this value, or up to the effective soil depth, if it is less than 100 cm, as shown in Figure 3.

In this approach, as a difference with former models, each factor of the Soil Productivity Index PI represents a specific soil quality that has to be evaluated and quantified through specific sub-factors, represented by direct or indirect measurable soil characteristics.

Evaluation of the Soil Productivity Index PI factors

Each one of the factors of the Soil Productivity Index PI is evaluated in terms of the respective most relevant sub-factor. The selection of the specific sub-factor depends on local conditions, generally the local climate, so the interaction between soils and climate is an important issue in this approach. In this sense, the following relations must be taken into account:

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

- In dry climate (P/ETP < 0.50): Factor A = subfactor A_1
- In humid climate (P/ETP > 2.00): Factor A = subfactor A_2
- In subhumid to dry climate (0.50 ≤ P/ETP ≤ 2.00): Factor A = most limiting value (the lowest numerical value) between subfactors 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 = subfactor B_1
- If the volumetric content of coarse fragments in the soil is greater than 30%, then Factor B = subfactor B_2

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

- In humid climate (P/ETP > 2.00): Factor C = subfactor C_1
- In dry climate (P/ETP < 0.50): Factor C = subfactor C_2
- In subhumid to dry climate (0.50 ≤ P/ETP ≤ 2.00): Factor C = most limiting value (lowest numerical value) between factors C_1 and C_2

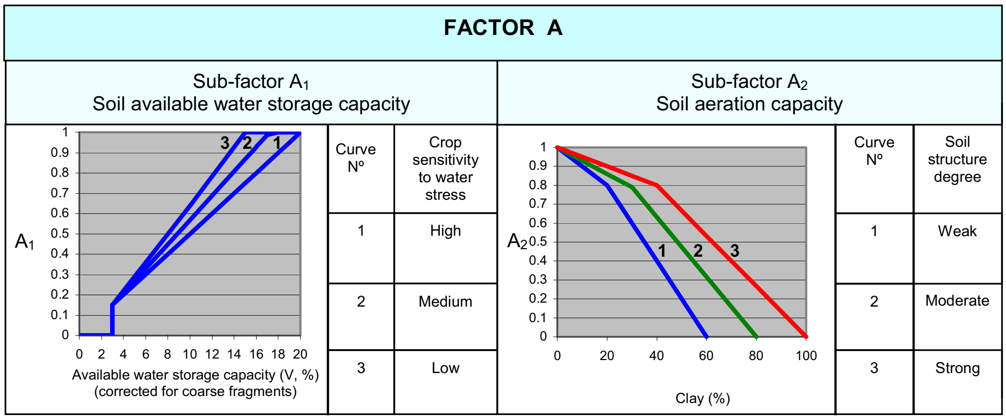
Factor K: This factor evaluates the relative importance of horizon *i* in the soil profile (weighting factor of the respective horizon). It is important to consider that Factor K, as shown in Figure 2, is the cumulative weighting factor of the soil profile up to the lower limit of horizon *i*, so the K value for the respective horizon *i* must be calculated as follows:

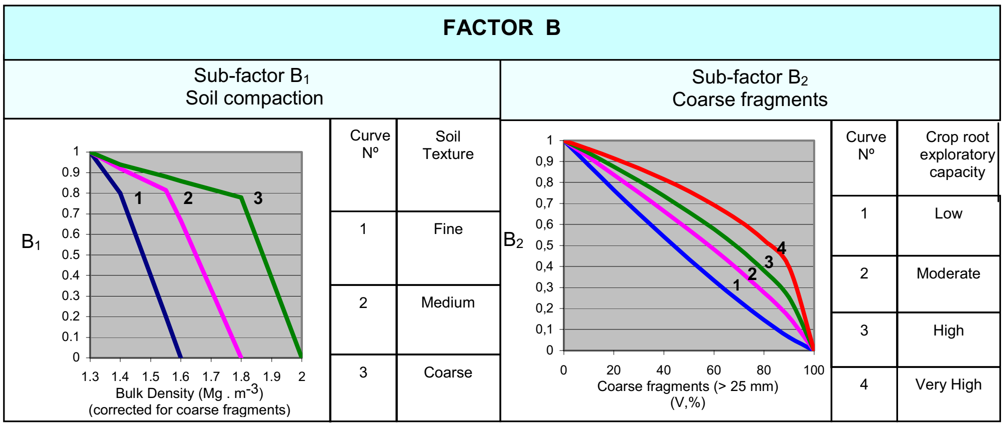
$$K_{(i)} = K_{cum\ (i)} - K_{cum\ (i-1)}$$

Figures 1 and 2 show the relations to calculate sub-factors of the Soil Productivity Index in conjunction with the above-mentioned relations. Relative values of soil productivity, estimated with the soil productivity index PI may be qualified as indicated in Table 1.

Table 1. Ranking soil productivity in terms the Soil Productivity Index PI

PI	Soil productivity
≤ 0.10	Low
0.11- 0.30	Moderate
0.31-0.50	High
> 0.50	Very high





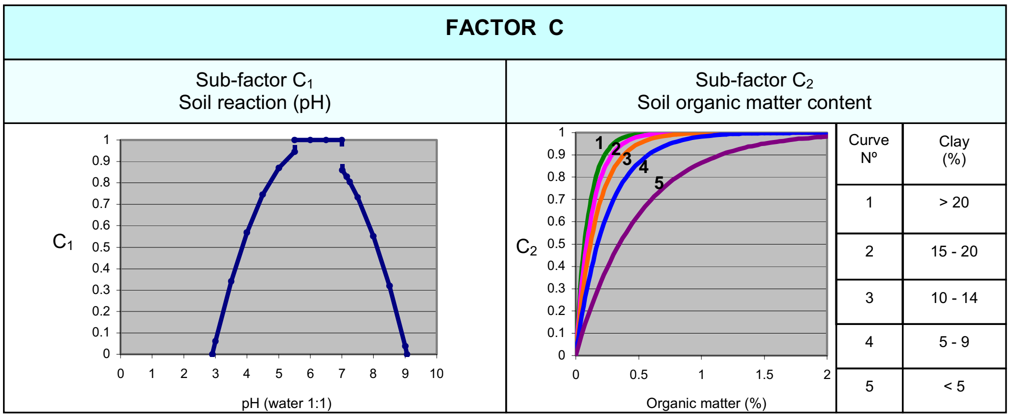


Figure 1. Factors A, B, C and respective sub-factors to evaluate the soil productivity index PI.

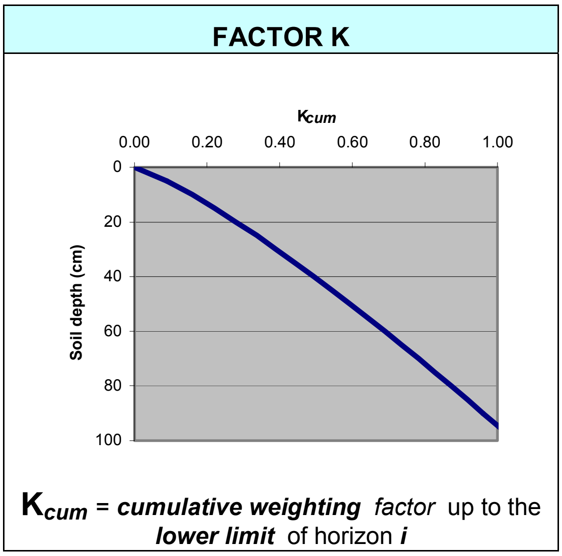


Figure 2. Factor K of the soil productivity index (weighting factor).

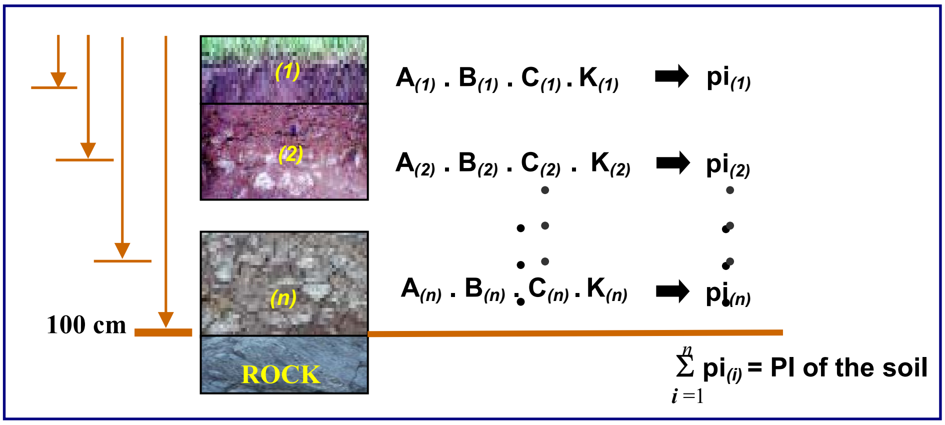


Figure 3. General procedure to calculate the soil productivity index (PI) of the soil.

SOIL LOSS TOLERANCE

Soil Loss Tolerance T is the maximum rate of annual soil erosion that may occur and still permit a high level of crop productivity to be obtained economically and indefinitely (Bergsma *et al*., 1996). Values of Soil Loss Tolerance T have been based on: 1.

Soil renewal rates, and 2.

Arbitrarily determined from published tables taking into account soil depth as other soil properties affecting root development. Currently used rates for tolerable soil loss of 10-12 $Mg.ha^{-1}.year^{-1}$ are far too high for most fragile tropical soils.

The (δ - H) Approach to Evaluate Soil Loss Tolerance (Delgado and López, 1998)

In this approach soil loss tolerance T is defined in terms of the following socio-economic variables: 1. The soil productivity permissible loss rate: δ (%) and 2. The planning horizon for sustainable land use: H (years). The method starts with the soil erosion vulnerability curve relating PI values and soil losses, as the example shown in Figure 4. Vulnerability is defined as the rate of change in productivity, measured by changes in PI values, per unit of soil removed by erosion.

To estimate soil loss tolerance (T) we apply the following equation:

$$PI_f = PI_i \, (1 - \delta)$$

where PI_f is the final soil productivity index after soil removal, PI_i the initial soil productivity index and δ the soil productivity permissible loss rate (%).

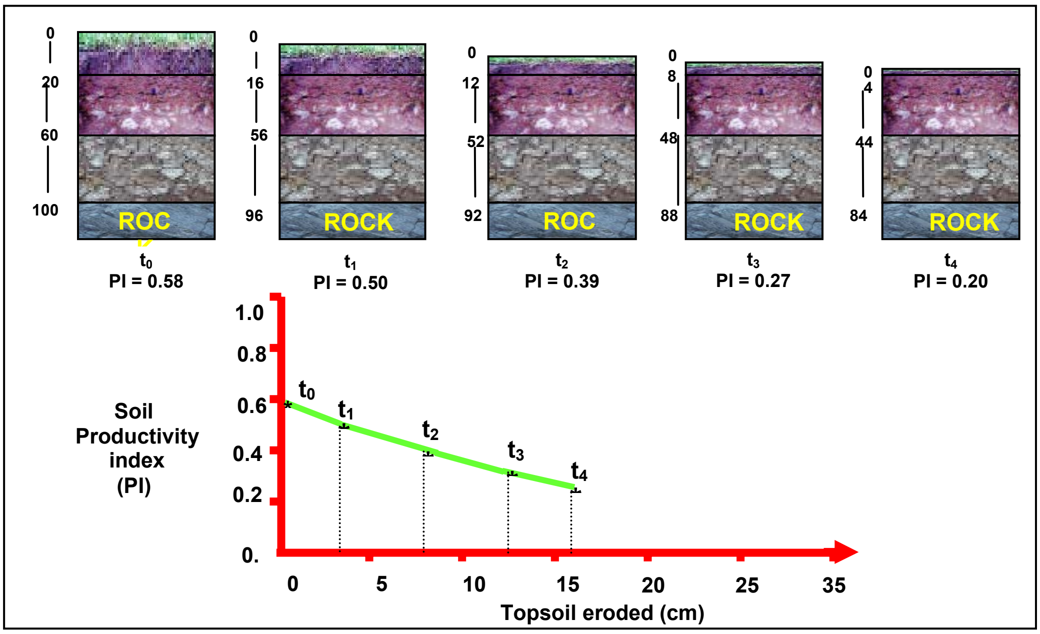


Figure 4. Soil vulnerability curve.

With the value of PI_f on the respective vulnerability curve, the correspondence amount of soil loss (cm) is obtained, which, when divided by a previously selected planning horizon (H, years) allows the calculation of soil loss tolerance (T, $cm.year^{-1}$). Knowing the values for bulk density ($Mg.m^{-3}$), soil loss tolerance can be expressed in $Mg.ha^{-1}$. The values δ and H are assumed as related to the needs and socio-economics premises adopted by land use planners and soil conservationists. Normally, δ varies between 0.05 to 0.10 (5-10%), and H could be assumed to be 100 to 200 years.

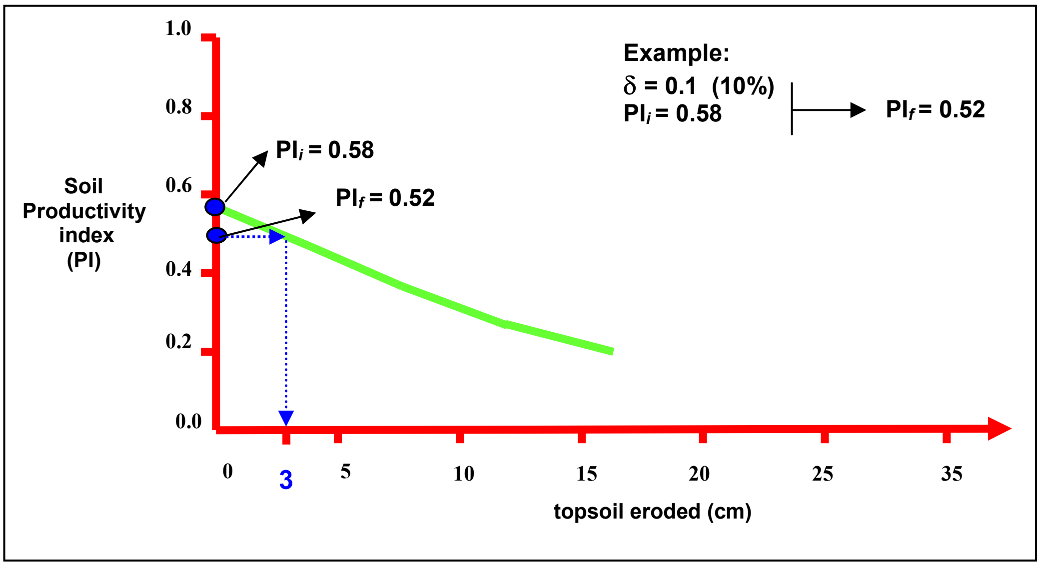


Figure 5. Soil erosion vulnerability curve showing the topsoil removed corresponding to a final productivity index PI_f.

Soil loss tolerance can be calculated from Figure 5 as follows: assume 3 cm of topsoil is eroded which is equivalent to a 10% soil productivity loss (3 cm = 0.03 m x 10,000 $m^2.ha^{-1}$ = 300 $m^3.ha^{-1}$). If the bulk density equals 1.40 $Mg.m^{-3}$, then (300 $m^3.ha^{-1}$ x 1.40 $Mg.m^{-3}$) equals a soil loss of 420 $Mg.ha^{-1}$.

This procedure allows to obtain a family of T values:

Planning horizon (H):				Soil loss tolerance (T_H):
50 years (T_{50})	⇒	420 Mg. ha^{-1} / 50 years	=	8.4 $Mg.ha^{-1}$. $year^{-1}$
100 years (T_{100})	⇒	420 Mg. ha^{-1} / 100 years	=	4.2 $Mg.ha^{-1}$. $year^{-1}$

200 years (T_{200}) $\Rightarrow$ 420 Mg. ha^{-1} / 200 years = 2.1 Mg.ha^{-1}. year^{-1}

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∞ (T_∞) $\Rightarrow$ 420 Mg. ha^{-1} / ∞ years = 0 Mg.ha^{-1}. year^{-1}

Table 2 shows the results of soil loss tolerance calculations from the application of the (δ - H) method to three sectors of "*Las Playitas*" watershed at the Venezuelan Andes.

Table 2. Soil loss tolerance T (Mg.ha^{-1}.year^{-1}) for two productivity permissible loss rate δ and two planning horizons H, on "Las Playitas", Mérida, Venezuela. (Delgado, Terrazas and López, 1998).

Sector 1				Sector 2				Sector 3			
PI_i = 0.227				PI_i = 0.304				PI_i = 0. 365			
δ = 5%		δ = 10%		δ = 5%		δ = 10%		δ = 5%		δ = 10%	
T_{100}	T_{200}	T_{100}	T_{200}	T_{100}	T_{200}	T_{100}	T_{200}	T_{100}	T_{200}	T_{100}	T_{200}
3.8	1.9	7.5	3.7	2.7	1.3	5.3	2.6	3.7	1.9	7.4	3.7

SOIL EROSION RISK

Soil erosion risk (or soil potential erosion), is the maximum soil loss in the absence of soil cover and conservation practices, that is to say, taking into account the interactions between the physical factors of the land: soil, climate and topography (Paez, 1994). The proposed model to evaluate this land quality is based on a modification from Delgado (1997). The approach takes into consideration three basic factors for estimating the susceptibility of a soil to water erosion: soil hydrological characteristics (infiltration-runoff ratio), rainfall aggressiveness and terrain slope. The Erosion Risk Index ERI is calculated with the following equation:

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

ERI is the Erosion Risk Index and has a value between 0 and 1, corresponding 1 to a land unit that presents the highest potential conditions for inducing water erosion processes; factor α evaluates the soil runoff potential; and factor η evaluates the impact of the terrain slope on erosion risk under different rainfall aggressiveness patterns. Each factor is evaluated ranging from 0 to 1, corresponding 1 to the condition that potentially promotes the highest occurrence of water erosion processes.

Evaluation of the Erosion Risk Index ERI factors

Factor α

This factor evaluates the soil runoff potencial beginning with granulometry and the soil structure degree of topsoil. The soil structure mainly includes the qualitative appraisal of its degree of development (weak, moderate or strong). Value α is obtained from Figure 6.

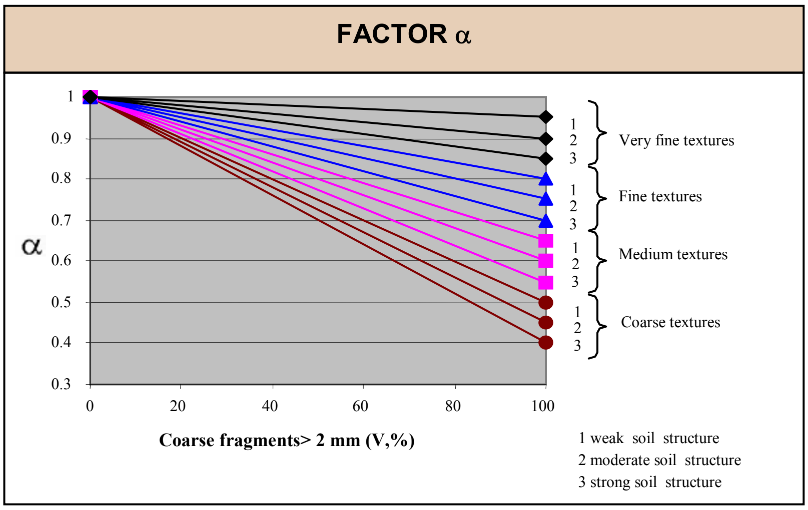

Figure 6. Factor α of the erosion risk index.

Factor η

This factor evaluates the impact of the topography and rainfall aggressiveness on erosion risk. The value of the factor is determined by the interaction between terrain slope (modal slope gradient) and the Fournier index (Fournier, 1960; quoted by FAO-PNUMA, 1980), which calculates the annual relative concentration of rain. This index has been correlated satisfactorily with annual discharges of sediment in tropical watersheds in several parts of the world (Morgan, 1986). It is determined with the following equation:

$$F = p^2 / P$$

where F is the Fournier Index, p the highest monthly precipitation (mm) and P the annual precipitation (mm). With it, Factor η value is obtained from Figure 7.

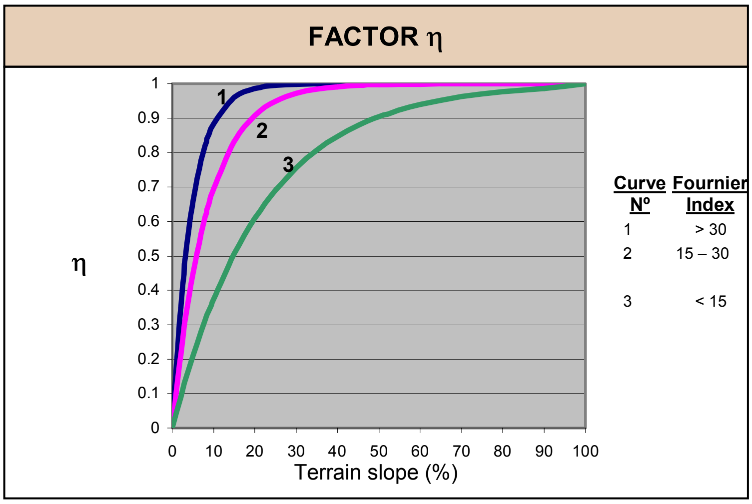

Figure 7. Factor η of the *erosion risk index.*

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 3.

Table 3. Ranking erosion risk in terms of values of the ERI.

ERI	Erosion risk
≤ 0.10	Low
0.11-0.30	Moderate
0.31-0.50	High
> 0.50	Very high

Land Classification System for tropical steeplands

Soil Productivity Index PI and Erosion Risk Index ERI have finally permitted establishing a classification system for agricultural lands in tropical mountains based on these two fundamental qualities. This system is similar to those developed by Sheng (1972) and Larson et al. (1988), and it is shown in Figure 8.

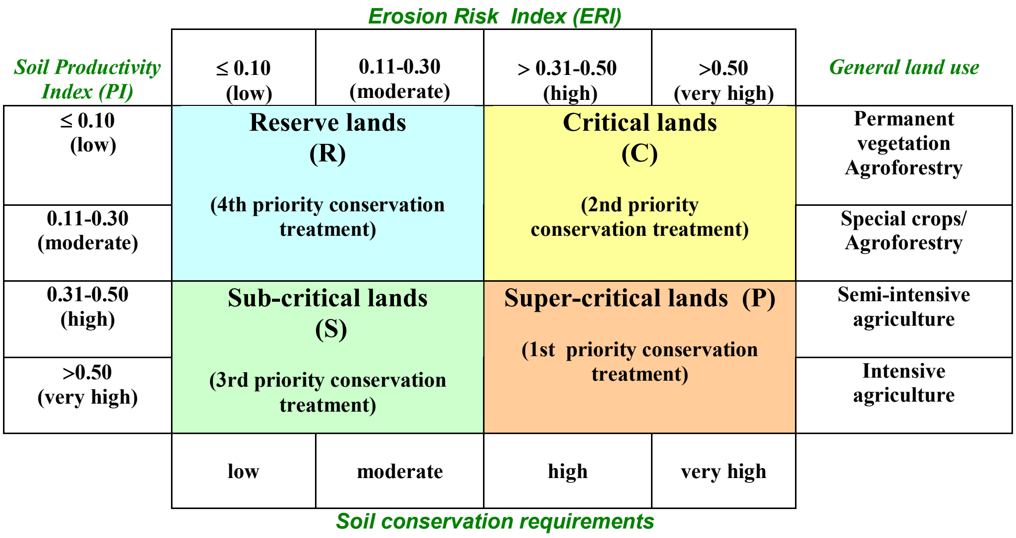

Figure 8. Land Classification System for soil conservation on tropical steeplands.

CLASSIFICATION OF SOIL MANAGEMENT AND CONSERVATION PRACTICES

The different conservation practices are grouped in three main categories indicated in Tables 4, 5 and 6.

Table 4 Category I : Practices for improving the soil productivity and soil resistance to erosion, as well as to reduce impacts from rainfall erosivity ("green practices").

Group I-A Soil improvement **(MS)**	**Group I-B** Ground covers and plant management **(MC)**
MS - 1 reduced-tillage	MC - 1 cover crops
MS - 2 vertical-tillage	MC - 2 mulching
MS - 3 mulch- tillage	MC - 3 high density planting
MS - 4 zero-tillage	MC - 4 multiple-cropping
MS - 5 ridge-tillage	MC - 5 crop rotations
MS - 6 ripping-tillage	MC - 6 intercropping
MS - 7 sub-soiling	MC - 7 tolerant crops
MS - 8 deep ploughing	MC - 8 perennial crops
MS - 9 soil fertilization	MC - 9 under shadow cropping
MS-10 residue incorporation	MC-10 pastures
MS-11 organic manures	MC-11 agroforestry
MS-12 green manures	MC-12 tree replanting and afforestation
MS-13 acid soil amendments	MC-13 natural re-vegetation
MS-14 sodic soil amendments	
MS-15 synthetic conditioners	

Table 5. Category II: Practices for reducing runoff impacts on hillsides ("blue practices").

Group II-A Slowing down runoff speed (AE)	Group II-B runoff catchment and/or transport (CE)
AE - 1 contour cropping AE - 2 hedgerows AE - 3 brush barriers AE - 4 strip cropping AE - 5 alley cropping	CE - 1 diversion channels CE - 2 hillside ditches CE - 3 retention ditches CE - 4 filtering ditches CE - 5 trench ditches CE - 6 diversion terraces CE - 7 retention terraces CE - 8 narrow-ridge terraces CE - 9 contour furrows
Group II-C slope length modification (LP)	Group II-D slope gradient modification (GP)
LP-1 wattlings LP-2 stone barriers LP-3 contour bunds LP-4 dams for gully control	GP-1 stone walls GP-2 continuous bench terraces GP-3 alternating bench terraces GP-4 individual terraces

Table 6. Category III: Complementary practices ("brown practices").

Complementary practices	
PC-1 stones removal PC-2 land levelling PC-3 trickle irrigation PC-4 sprinkler irrigation PC-5 surface drainage	PC-6 subsurface drainage PC-7 firebreaks PC-8 protective fences PC-9 windbreaks PC-10 animal paths

Selection of soil conservation practices

In terms of the main limitations detected in the analysis of factors corresponding to soil productivity, in Table 7 there are some management and conservation practices that could be used to improve it.

Table 7. Identification of some soil management and conservation practices for reducing soil productivity limitations.

limiting soil condition	limiting factor	Limiting sub-factor	soil management and conservation practices (*)
air-water ratios	**A**	**A_1** (available water capacity)	**MS-3, MS-4, MS-11, MS-12, MS-15, CE-3, CE-4, CE-5, CE-7, PC-3, PC-4**
		A_2 (aeration capacity)	**MS-1, MS-5, MS-8, MS-10, MS-15, MC-7, CE-1, CE-2, CE-6, PC-2, PC-5, PC-6**
mechanical resistances for root exploration	**B**	**B_1** (bulk density)	**MS-2, MS-6, MS-7, MS-8, MS-10, MS-11, MS-12, MS-15**
		B_2 (coarse fragments)	**PC-1, MS-1, MS-2, MC-4, MC-6, MC-7, MC-8, MC-10, MC-11, MC-12**
potential fertility	**C**	**C_1** (pH)	**MS-9, MS-10, MS-11, MS-12, MS-13, MC-5, MC-7, MC-10, MC-11**
		C_2 (organic matter)	**MS-10, MS-11, MS-12, MS-14, MC-7, MC-10, PC-7**

(*) codes are explained in Tables 4, 5 and 6

In terms of the main limitations detected in the analysis of factors corresponding to erosion risk, in Table 8 some management and conservation practices are mentioned that could be used to reduce such risks or to improve land conditions.

Table 8. Identification of some soil management and conservation practices for reducing limitations.

Limiting land condition	Limiting factor	Soil management and conservation practices (*)
soil runoff potential	α	**MS-1, MS-2, MS-3, MS-4, MS-6, MS-7, MS-8, MS-10, MS-11, MS-12, MS-15, AE-1, AE-2, AE-3, AE-4, CE-1, CE-2, CE-6, CE-9, PC-5**
rainfall aggressiveness & terrain slope	η	*for rainfall aggressiveness* **:** **MS-3, MS-4, MS-5, MS-12, MC-1, MC-2, MC-3, MC-4, MC-5, MC-6, MC-8, MC-9, MC-10, MC-11, MC-12, MC-13**
		for terrain slope **:** **CE-8, LP-1, LP-2, LP-3, LP-4, GP-1, GP-2, GP-3, GP-4, PC-3, PC-4, PC-8, PC-10**

(*) codes are explained in Tables 4, 5, and 6

CONCLUSIONS

This paper underlines the role, importance and applications of soil physics on land use planning and soil conservation on tropical steeplands.
The relevance of soil productivity and erosion risk are emphasized as important qualities that allow integrating several relevant physical characteristics of these lands, as well as to adequately formulate a system adapted to the particular conditions of tropical mountains for the identification and selection of the most appropriate alternatives for soil conservation programs.

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