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DEVELOPMENT AND EVALUATION OF A NEW SOIL EROSION-PRODUCTIVITY INDEX MODEL (SEPIM)

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ABSTRACT

A soil erosion-productivity model which considers the effect of soil water storage capacity, crop evapotranspiration, soil chemical and physical properties important for crop growth has been developed. The model is shown to give good predictions and it promises to be an improvement over the former productivity Index (PI). It also promises to give more reliable results than the currently used models which consider only soil water storage capacity and crop evapotranspiration.

INTRODUCTION

Many models have developed for predicting loss in soil productivity as caused by erosion [8, 13, 14, 17, 18, 19]. However, all the models still need further validation and/or modification [13].

The sophistication of the existing soil erosion-productivity models is quite variable. They vary from deterministic mathematical models like the Erosion Productivity Impact Calculator (EPIC) [8, 19] simulating storm-based soil erosion, solute movement over and through soil and soil fertility-crop growth, to models that only simulate reduction of soil water storage capacity by continued soil erosion [17, 18]. The sophisticated models such as EPIC require database not readily available in many developing countries [1, 7]. Simple models like those simulating the effect of soil erosion on soil water storage capacity cannot always give accurate predictions of the effect of soil erosion on soil-crop productivity because they do not take into account the physical and chemical properties of soils important for crop growth and affected by soil erosion.

Soil erosion affects many soil characteristics which are related to crop growth and yield [13, 15, 16]. Continued soil erosion results in reduced rooting depth and soil water storage capacity, crusting, soil compaction, change in root zone cation exchange capacity (CEC), aluminium and manganese toxicity, soil acidity/alkalinity and deterioration of soil biological properties [11, 13; 16, 17]. Unless a model takes into account most of the important factors affecting crop growth that are affected by soil erosion its accuracy will remain unreliable. The model presented in this paper takes into account most of the important parameters affecting crop growth and that are affected by soil erosion. The parameters considered in the model are also relatively available in developing countries [10].

THE DEVELOPMENT OF THE SOIL EROSION-PRODUCTIVITY INDEX MODEL

The developed new soil erosion-productivity index model (SEPIM) is a hybrid of the productivity index (PI) [6, 14] and the models simulating soil moisture availability to plants and yield relationships [17, 18]. The PI model as originally developed [6] and subsequently modified [14] is:-

$$PI = \Sigma^{n}_{i=1} (A_i *C_i *D_i *E_i *RI_i) \qquad (1)$$

Where A_i = sufficiency of soil water holding capacity in the ith layer,
C_i = sufficiency of soil bulk density (and aeration) in the ith layer.
D_i = sufficiency of soil pH of the ith layer,
E_i = sufficiency of soil electrical conductivity (salinity) in the ith layer,
RI_i = root weighting factor of the ith soil layer, and
n = the number of soil layers of the root zone depth.

With the exception of A_i sufficiency which is based on assumption only, all the other parameters in the PI model are based on research findings of the effects of respective soil properties on root growth which in turn is assumed to be related to crop growth and production as has been established from research [6]. The A_i sufficiency in the PI model is not linked to crop evapotranspiration requirements. Thus, this factor alone can explain the variable performance of the PI model in predicting the effects of erosion on soil productivity as reported by many authors [4, 6, 14].

The models simulating soil moisture availability to plants and yield relationships as affected by soil erosion use the equation developed by Doorenbos and Kassam [3].

$$Y_a/Y_m = 1-k_y(1-ET_a/ET_m) \qquad (2)$$

Where Y_a = actual crop yield (t/ha),

Y_m = potential crop yield under water constraint-free conditions (t/ha),

k_y = empirical yield response factor for a given crop type and stage of development,

ET_a = actual crop evapotranspiration for the crop development stage under consideration,

ET_m = potential evapotranspiration of a disease free crop under water constraint-free conditions.

The SEPIM was developed by removing parameters A_i in the PI model with a weak scientific basis and then combining the equation formed by the remaining parameters in equation 1 with equation 2 as shown in equation 3.

$$PP = (1-k_y(1-ET_a/ET_m))\Sigma^n_{i=1}(C_i*D_i*E_i*RI_i) \qquad (3)$$

Where PP = productivity potential of a soil ranging from 0 and 1.0)

Equation 2 or the left hand side component of equation 3 involves determining actual and potential evapotranspiration values and the crop response factor. Many equations and/or procedures are available for estimating crop evapotranspiration values for different climatic conditions [3]. The yield response factor is variable from crop to crop and at different stages of development [3, 18], however, where enough data is lacking estimates given by Doorenbos and Kassam [3] are reasonably sufficient.

The right hand side component of SEPIM (i.e the one formed from the PI model) uses parameters evaluated as in the PI model [10, 14]. To determine the sufficiency of bulk density, C_i, one has to obtain non-limiting, critical and root-limiting bulk densities which depend on soil family texture classes [6, 14]. These are given in Table 1. For each soil textural class with a given bulk density one determines its relative position on the x-axis of Figure 1 and then the sufficiency value is read relative to the y-axis. The bulk density sufficiency value determined from Figure 1 is adjusted to take into account permeability rates (for water and air by equation:

$$C_i = 1-(1 - SUFFg)\beta \qquad (4)$$

Where SUFFg = sufficiency of bulk density from Fig. 1,

β = adjustment factor determined from Table 2.

Table 1 Nonlimiting, critical and root B limiting bulk densities for different family texture classes (source: Pierce et al., 1983).

Family Texture class	Nonlimiting Bulk Density	Critical Bulk Density (g/cm^3)	Root -Illimiting Bulk Density
Sandy	1.60	1.69	1.85
Coarse loamy	1.50	1.63	1.80
Fine loamy	1.46	1.67	1.78
Coarse silt	1.43	1.67	1.79
Fine silt	1.34	1.54	1.65
Clayey: 35 - 45 %	1.40	1.49	1.58
> 45 %	1.30	1.39	1.47

Table 2 Adjustment factors (â) for sufficiency of bulk density used in equation 4 (source: Pierce et al., 1983)

Family Texture Class	Permeability (mm/hr)				
	< 1.5	1.5 - 5.1	5.1 - 15.2	15.2 - 0.8	> 50.8
Fine loamy	1.0	1.0	0.9	0.7	0.5
Coarse silt	1.0	1.0	1.0	0.9	0.7
Fine silt	1.0	1.0	0.9	0.7	0.5
clay: 35- 60 %	1.0	0.9	0.7	0.6	0.5
> 60 %	1.0	0.8	0.6	0.5	0.4

The pH sufficiency, D_i, is determined using the following equations [14]

$$\begin{aligned} D_i &= 0.75 \text{ (for pH} > 8.0) \\ &= 2.086-0.167\text{pH (for } 6.5 < \text{pH} < 8.0) \\ &= 1.0 \text{ (for } 5.0 < \text{pH} < 6.5) \\ &= 0.12 + 0.16\text{pH (for pH: 5.0 B 5.5)} \\ &= 0.446\text{pH B 1.31 (for pH: 2.9 B 5.0)} \\ &= 0.0 \text{ (for pH} < 2.9) \end{aligned} \quad (5)$$

The sufficiency of electrical conductivity, E_i, for soils affected by salinity is determined using equation (6).

$$E_i = 1.14 - 0.07\ EC \quad (6)$$

Where EC = electrical conductivity (mmhos/cm)

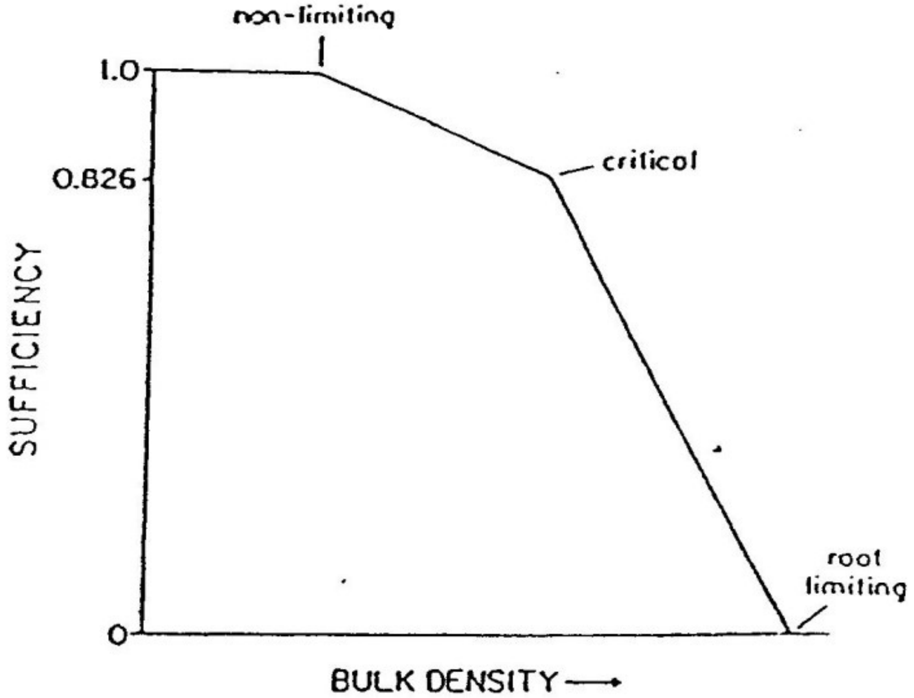

Fig. 1 Sufficiency of bulk density used in the soil erosion-productivity, PI, model

The weighting factor, RI_i, is based on the seasonal distribution of plant water uptake from different horizons within the root zone. The equation predicting the profile of fractional water uptake from a moist soil is given by [4]:

$$RI_i = 0.152 \log(R + R^2 + 6.45)^{0.5}) - 0.152 \log(D + (D^2 + 6.45)^{0.5}) \text{.........} \qquad (7)$$

Where RI_i = fractional seasonal water uptake from a given soil depth, D. Summation of RI_i values for all root zone depth sections under consideration add up to 1.0

R = maximum plant rooting depth.

EVALUATION OF THE SEPIM

Materials and Methods

The data for evaluating the soil erosion productivity index model (SEPIM) were obtained from runoff plots set up by Soil Erosion Research and Water Harvesting Research Programmes at the Agricultural Research Institute(ARI), Hombolo, located at 35 km north east of Dodoma in the central semi-arid regions of Tanzania [5, 9, 10] and the soil survey report by De Pauw et al. [2]. Both of the research programmes are run by the Department of Agricultural Engineering and Land Planning, Sokoine University of Agriculture, Morogoro, Tanzania. Data collected by the two research programmes and used to evaluate the SEPIM were rainfall storm volumes, storm runoff volumes, soil pH, soil texture, soil bulk density, soil permeability and sorghum crop growth and yields from the runoff plots for the 1994 and 1995 rainy seasons. The runoff plots from which the data were obtained for both research programmes had tillage treatments as shown in Table 5 and similar inorganic fertiliser applications at planting and after first weeding. The data obtained from the soil survey report by De Pauw et al. [2] and used in the SEPIM evaluation were soil water holding capacities and potential evapotranspiration values.

The rainfall storm volumes and runoff volumes obtained from the two research programmes were used to calculate effective rainfall volumes (rainfall volumes minus runoff volumes and percolation volumes in excess of soil water holding capacities in the root zones). Actual crop (sorghum) evapotranspiration values were determined from potential evapotranspiration values calculated by De Pauw et al. [2] using Penman [12] method and meteorological data from Dodoma Airport together with the actual root zone soil water availability at the two research sites for the two rainy seasons (i.e 1994 and 1995).

Table 3 Root and shoot growth characteristics for "serena or tegemeo" sorghum varieties (Modified from De Pauw et al., 1983)

Growth stage	Weeks of growth cycle	Rooting depth (cm)
Vegetative	1 - 3	30
	4 - 6	100
Flowering	7 - 8	100
Yield formation	9 - 13	150
Ripening	14 - 15	150

Crop evapotranspiration depends on root zone water availability as well as the stage of crop development. The root and shoot growth characteristics of the sorghum crop variety (Tegemeo or Serena) grown at the two runoff plots research sites used to calculate actual crop evapotranspiration [3] are shown in Table 3. During the calculations of the actual crop evapotranspiration values it was assumed that evapotranspiration dropped linearly from potential evapotranspiration levels in proportion to soil water availability after water depletion has reached 50% of the soil water storage capacity as shown in Fig. 2. It was also assumed that lateral subsurface water flows from outside the runoff plots were negligible. The calculations of crop evapotranspiration values were based on 10 days interval grouped rainfall volumes to shorten the calculations. The actual yield responses for different water consumptive regimes were estimated using the relationships between relative evapotranspiration deficits and relative

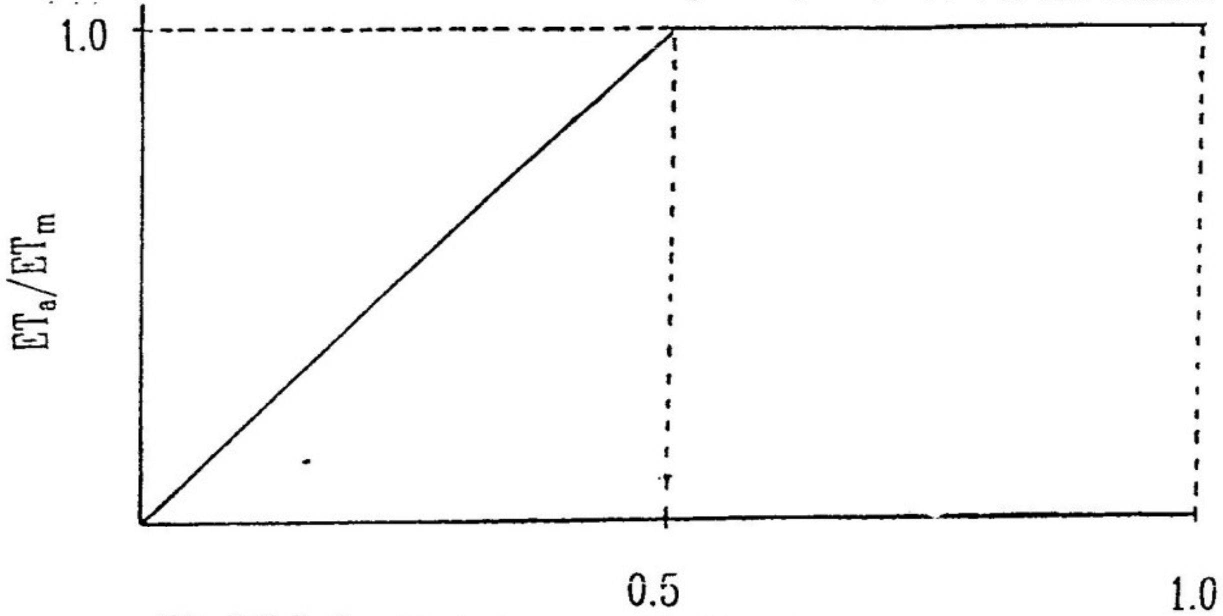

Fig. 2 Relationship between available soil water and actual evapotranspiration

All the parameters in the right hand side component of equation 3, except E_i were determined as outlined above. The E_i parameter was assumed equal to 1.0 because the soils at the water harvesting and soil erosion research sites have no salinity problems.

The soil crop productivity index values of the equation 3 obtained as explained above were regressed against sorghum yield records from the two research programmes to evaluate the SEPIM.

Results and Discussion

The soil properties and the derived parameters of the soil erosion-productivity model(s) are given in Table 4. The soil erosion-productivity calculation results are given in Table 5. The regression analysis performed to evaluate the

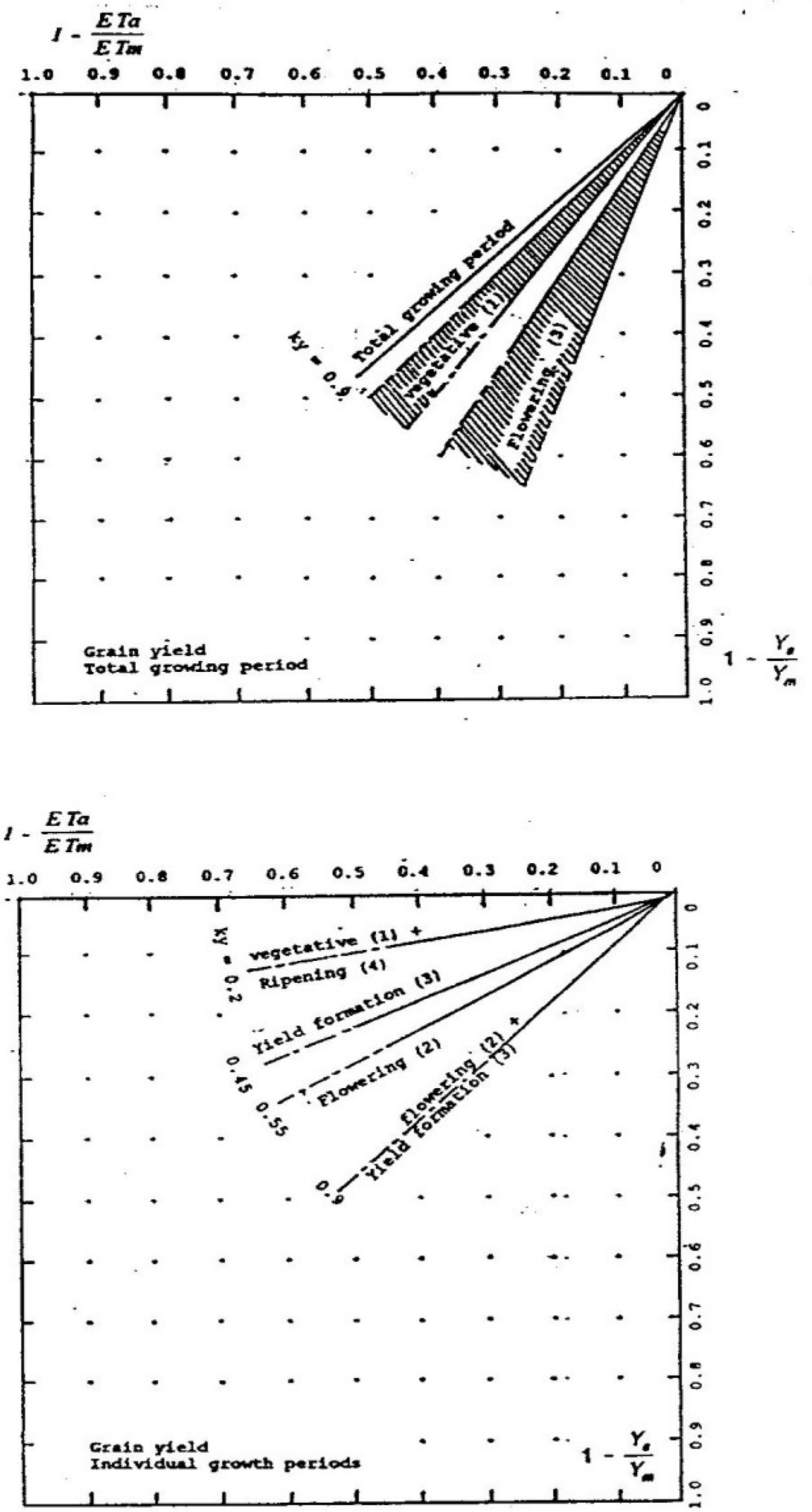

Fig. 3 Relationship between relative yield decrease (1-y_a/y_m) and relative evapotranspiration deficit (1-ET_a/ET_m) for sorghum [3]

productivity model(s) resulted in equations 8, 9, 10, 11 and 12. Plots of regression lines for equations 8 and 9 are shown in Figs. 4 and 5 respectively.

Table 4 Soil properties at the Hombolo soil erosion and water harvesting research sites used to determine parameters of the productivity model (equ. 3).

Soil erosion research site*				Water harvesting site*			
Horizon	Texture	Db (g/cm^3)	pH**	Horizon	Texture	Db (g/cm^3)	pH**
00-10 cm	LS	1.52	3.8	00-12 cm	LS	1.52	4.2
10-19 cm	SL	1.52	3.8	12-28 cm	SL	1.52	4.2
19-39 cm	SL	1.60	3.8	28-46 cm	SL	1.60	4.3
39-100cm	SCL	1.60	3.8	46-102cm	SCL	1.60	5.0

* Rootzone water holding capacity for the soils at erosion and water harvesting sites were 70 mm/m and 100 mm/m respectively (De Pauw et al., 1983).

** pH($CaCl_2$) determined by multiplying measured pH(H_2O) results at the two sites with a factor of 0.84 as estimated from the pH measurements in the report by De Pauw et al. (1983).

Table 5 Soil erosion-productivity calculation results for the water harvesting and soil erosion research sites

Site	$E^{n}_{i=1}C_i*DRI_i$	Ya/Ym		PP_{ay}		crop yield (t/ha)	
		1994	1995	1994	1995	1994	1995
Soil erosion							
Plot No. 2	0.47	-	0.6	-	0.3	-	1.292
Plot No. 4	0.47	-	0.6	-	0.3	-	1.378
Plot No. 5	0.47	-	0.6	-	0.3	-	1.088
Water harvesting							
Zero tillage	0.60	0.9	0.7	0.54	0.42	3.159	2.000
Handhoe tillage	0.60	0.9	0.7	0.54	0.42	3.798	1.684
Tractor tillage	0.60	0.9	0.7	0.54	0.42	2.991	1.723

$$\text{Yield} = 8.5972PP - 1.4871 \text{ (for 1994 \& 1995 rainy seasons)} \quad (r^2 = 0.87, n = 9). \tag{8}$$

$$\text{Yield} = 6.996Ya/Ym - 2.9923 \text{ (for 1994 \& 1995 rainy seasons)} \quad (r^2 = 0.93, n = 9) \tag{9}$$

$$\text{Yield} = 4.5817PP - 0.1218 \text{ (for 1995 rainy season)} \tag{10}$$

$(r^2 = 0.81, n = 6)$

$$\text{Yield} = 5.4980Ya/Ym - 2.046 \text{ (for 1995 rainy season)} \quad (11)$$

$(r^2 = 0.81, n = 6)$

$$\text{Yield} = 4.229\ \Sigma^{n}_{i=1} (C_i{*}D_i{*}RI_i) \text{ (for 1995 rainy season)} \quad (12)$$

$(r^2 = 0.81, n = 6)$

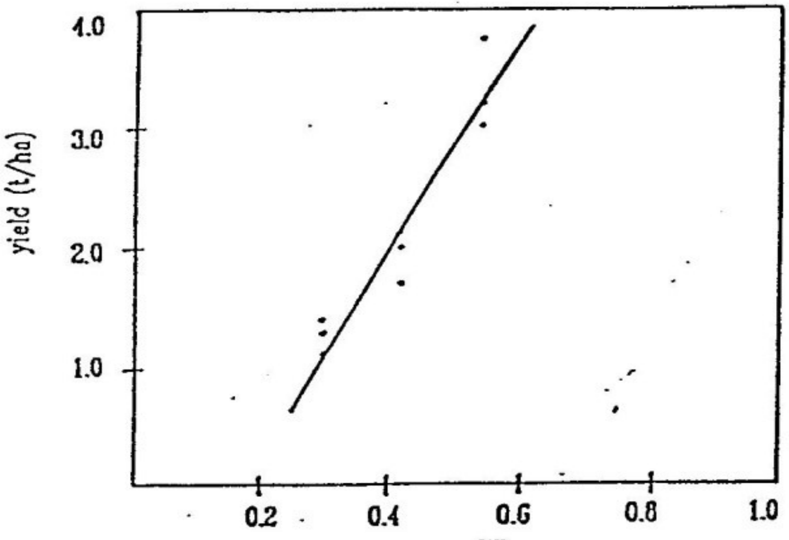

Fig. 4 Measured yield versus predicted fractional crop yield potential using equation 8

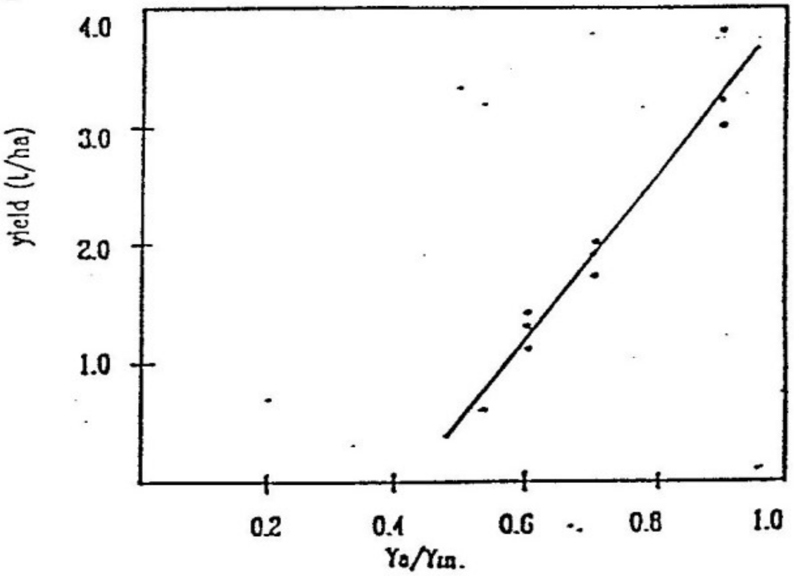

Fig. 5 Measured yield versus predicted fractional crop yield potential using equation 9

As shown in equation 8, the SEPIM was able to explain about 87% of the variations in sorghum yields for the two rainy seasons while the actual evapotranspiration alone explain about 93% of the sorghum yield variations (see equation 9). Further regression on the six yield data of 1995 was done to check whether the observations in equations 8 and 9 were consistent. The regression results show that soil parameters affecting crop development and yield (equation 12), actual evapotranspiration (equation 11) and the SEPIM (equation 10) can explain about 81% of the yield variations. Thus the accuracy difference between the SEPIM model (equation 8) and that of Doorenbos equation (equation 9) in explaining sorghum yield variations can be due to experimental error, especially when considered that limited data was used to test the models and average long term potential evapotranspiration was used to calculate actual crop evapotranspiration for the two cropping seasons.

From the regression results of equations 8 to 12 it can be concluded that where soil erosion is sustained over a long period and the end result is shallow rooting depth and exposure of subsoils whose physical and chemical properties important for crop growth do not practically differ from the eroded top soils, the availability of water to plants is a sufficient measure of the effect of erosion on crop productivity. However, where the physical and chemical properties of the exposed subsoils differ from those of the eroded top soils, both the reduction in soil water available to plant and the soil properties are important for evaluating the effect of soil erosion on crop productivity.

The SEPIM promises to be an improvement over the productivity index (PI) model [6, 14]. It also promises to give more reliable results than the soil life span model [17] or the water budget approach proposed by Timlin et al. [18], both of which only use the reduction of soil water holding capacities by soil erosion in simulating the loss in soil productivity.

The data used to evaluate the SEPIM model is limited. Further investigation for a wider range of soils, crops and climates are thus needed to ascertain the accuracy of the SEPIM and possibly improve the methods used to estimate its soil parameter values and/or change its structural form [4] despite the fact that extensive data used by Pierce et al. [14] show the methods to be accurate.

CONCLUSION

A soil erosion-productivity model taking into account important factors affected by erosion and affecting soil productivity has been developed. The model promises to give reliable prediction and requires data base relatively available even in developing countries. Data used to evaluate the model was limited. More research data is still needed to ascertain its accuracy and possibly modify it.

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