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Stability of Agricultural Ecosystems: Application of a Simple Model for Soil Erosion Assessment

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STABILITY OF AGRICULTURAL ECOSYSTEMS: APPLICATION OF A SIMPLE MODEL FOR SOIL EROSION ASSESSMENT

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PREFACE

The evaluation of the consequences of interaction between man and environment is one of the important problems which attracts many scientists. In investigating this problem, special attention is paid usually to the usage of land resources. During 1982, IIASA's "Land and Landcover Resources" task within the Resources and Environment Area (REN) investigated the problem "Stability of Ecosystem". One of the fourth topic of investigations is devoted (in particular) to the problems of "Stability of Agroecosystems". Cooperation with the researchers from the National College of Agricultural Engineering (Silsoe, Bedford) was done to clarify this problem. The main interest was connected with the influence of natural and man-made perturbations on the erosion process for a long period of time when the result of relatively small perturbations can lead to the situation where the agroecosystems are getting unstable. A simple model for soil erosion assessment was suggested by the authors to analyze the stability of agricultural ecosystems. Documentation and validation of this model was published as IIASA's Collaborative Papers CP-82-59 and CP-82-76. This is the third and final collaborative paper, where the implementation of the above mentioned model was made in tropical rain forest and the stability of agroecosystems was investigated as a function of the soil conditions under climatic perturbations, different land use and different time horizon.

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ABSTRACT

The stability of the erosion system in a tropical rain forest environment is investigated using the model previously described by Morgan, Morgan and Finney (1982) and validated by Morgan and Finney (1982). Simulations are carried out for the natural primary forest cover, commercial timber extraction and the agricultural ecosystems of rubber cultivation, shifting cultivation with sixteen-year, fourteen-year and four-year cycles, and continuous rotational cropping of groundnuts, maize and potatoes. The model is operated for five slope steepnesses using a hundred-year synthetic sequence of rainfall data generated by Monte Carlo analysis. Erosional stability is expressed in terms of changes in rooting or top soil depth. Using the model it is possible to distinguish between three broad states of biostasy, rhexistasy and homeostasy, representing increasing, decreasing and stable rooting depths respectively. Detailed examination of the magnitudes of the change in rooting depth in response to perturbations in the system and the length of time required for recovery can show the extent to which systems in a state of or close to homeostasy are potentially unstable.

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STABILITY OF AGRICULTURAL ECOSYSTEMS: APPLICATION OF A SIMPLE MODEL FOR SOIL EROSION ASSESSMENT.

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INTRODUCTION

Previous papers have documented (Morgan, Morgan and Finney, 1982) and validated (Morgan and Finney, 1982) a simple model for assessing the stability of the soil erosion component in agricultural ecosystems. This paper illustrates the application of this model.

Simulations are carried out to analyse the effects of both climatic and man-induced disturbances or perturbations on the stability of the erosion system in a tropical rain forest environment. In interpreting the results, attention is given to the resilience of the system in terms of the time needed for its recovery to disturbances of different frequencies and magnitudes as well as to the types of disturbance required to trigger an unstable and irreversible trend of continuous decreases in soil depth until all the soil is remcved.

EXPERIMENTAL STRATEGY

The objective of this phase of research on the model is to investigate its potential for indicating the likely response of erosion systems to both natural and man-made disturbances. It is not the intention to examine a specific erosion system in detail with a view to determining various management options, although the model could be used in that way. Instead, the aim is to demonstrate, through a series of simulations, the ability of the model to provide information about the sensitivity of the erosional environment to disturbances of various kinds. Nevertheless, it was felt desirable to make the simulation as realistic as possible.

It was decided to use data from Malaysia, a country to which the model had been previously and successfully applied and for which good quality data were readily available (Morgan, Hatch and Sulaiman, 1982). The selection of Malaysia for analysis has the added advantage of providing an opportunity of examining a tropical rain forest, an environment which is known to be particularly sensitive to change and under threat from commercial timber exploitation and agriculture.

The strategy adopted was firstly to examine the stability of the erosion system under a cover of primary rain forest and then to investigate the effects of disturbances of different magnitudes and frequencies upon it. A distinction was made between natural disturbances of climatic origin and those that are man-induced and which are expressed as different types of landuse. Distinctions were also made between continuous regular perturbations, continuous random perturbations and individual disturbances of various magnitudes and frequencies. The effects of the perturbations associated with landuse were also examined for a range of slopes.

The experiment comprised seven landuse types, five slopes and one set of climatic perturbations, making a total of thirty-five simulations. All simulations were carried out for a period of one hundred years.

SIMULATIONS

Reference conditions

Simulations were carried out for a typical area in the undulating hill country of Selangor, Malaysia, to the south and west of Kuala Lumpur. The Padang Besar Soil Series was taken as a representative soil condition. It is a kaolinitic clay, classified as an isohyperthermic petroferric tropodult in the US Soil Taxonomy but the surface soil layer is a thin, 9-I7cm, sandy clay loam. This overlies a sandy clay band containing up to I0 per cent petroplinthite. The soil becomes clayey at depth and the petroplinthite content increases to 70 per cent.

Input parameter values for bulk density (BD=I.28) and the moisture storage at field capacity (%w/w at I/3-bar; MS=0.26) are measured for the surface soil (University of Agriculture, Malaysia, I979). A value of 0.I5m was chosen as the initial rooting depth (RD) in all simulations. This is a typical value for a forest cover (Morgan and Finney, I982) and all the simulations were designed to apply to a rain forest throughout or to examine the effects of clearing a long-standing forest cover for other uses. The input value of 0.3 for the soil detachability index (K) is based on previous trials with the model for the chosen soil (Morgan, Hatch and Sulaiman, I982).

Very limited information is available on which to base a value for the rock weathering rate (W). Rates cited by Ollier (I975) for the humid tropics range from 0.002 to 0.6 mm per year. Figures quoted by Douglas (I969) indicate a solutional lowering of the land surface by 0.00I to 0.0I mm per year by the removal of silica alone and Carson and Kirkby (I972) give a generalised value of 0.4 mm per year for total solutional lowering in environments with a mean annual temperature of 25°C and a mean annual rainfall of 2500 mm. A value of 0.02 mm per year has been chosen for the simulations described in this paper.

Slope conditions

Arbitrary values of slope steepness were selected at 2°,4°,8°,I6° and 34° which gives a geometric progression in terms of their sine values.

Rainfall perturbations

The effects of annual variations in rainfall amount and number of rain days were examined using a synthetic sequence of one hundred years of rainfall data typical of a humid tropical climate. Annual rainfall totals were generated by a Monte Carlo method from a log normal distribution with the same mean and standard deviation as observed in an eleven-year sequence of annual rainfall values averaged for the whole of Selangor (Chia I968).

Table 1 Synthetic rainfall data

Column 1 = year of simulation. Column 2 = annual rainfall (RAIN).
Column 3 = number of rain days (RN).

1	2029	181	51	2348	191
2	2425	195	52	2380	192
3	2413	180	53	2210	184
4	2209	181	54	2296	180
5	2161	183	55	2165	178
6	2479	193	56	2725	197
7	2305	181	57	2312	186
8	2163	181	58	2222	189
9	2152	171	59	2098	181
10	2419	186	60	2256	177
11	2752	194	61	2084	174
12	2740	198	62	2382	190
13	2282	191	63	2345	188
14	2154	192	64	2603	187
15	2195	178	65	2473	188
16	2475	199	66	2430	189
17	2214	186	67	2365	174
18	2323	182	68	2744	202
19	2556	187	69	2106	181
20	2327	180	70	2420	196
21	2033	175	71	2184	178
22	2547	193	72	2371	192
23	2205	194	73	2305	190
24	2408	189	74	2356	195
25	2426	187	75	2216	193
26	2543	192	76	2395	189
27	2368	196	77	2082	182
28	2460	197	78	2175	179
29	2696	209	79	2316	191
30	2514	187	80	2662	189
31	2154	170	81	2178	185
32	2099	185	82	2257	183
33	2362	178	83	2297	190
34	1974	179	84	2230	181
35	2052	192	85	2483	194
36	2520	191	86	2391	182
37	2669	182	87	2377	193
38	2362	185	88	2132	176
39	2222	173	89	2499	188
40	2110	183	90	2367	183
41	2389	199	91	2265	178
42	2313	182	92	2633	201
43	2386	179	93	2021	182
44	2477	196	94	2356	195
45	2483	192	95	2554	200
46	2368	182	96	2087	184
47	2512	193	97	2128	186
48	2440	199	98	2493	199
49	2406	178	99	2254	187
50	2421	189	100	2425	178

The number of rain days were also obtained by a Monte Carlo method based on the strong relationship (r=0.75) between the number of rain days and the annual rainfall total observed in a nine-year sequence of data for Kuala Lumpur airport (Chia, I973).

The rainfall data are representative of a continuous sequence of random, frequent and small perturbations such as are likely to arise from year-to-year variations in the rainfall regime (Table I). The mean annual rainfall is 234I mm. Annual totals range from I974 to 2752 mm and the number of rain days from I70 to 209. The most extreme conditions occur in years eleven and twelve with rainfall amounts of 2752 and 2740 and numbers of rain days of I94 and I98 respectively. These rainfall totals and rain day combinations have a return period of about fifty years.

Throughout the simulations a value of 25.0 mm per hour is used for rainfall intensity (INTENS); this is a typical value for erosive rains in tropical regions.

Landuse perturbations

Eight landuse strategies were devised to simulate the effects of no perturbations, single perturbations of various magnitudes and frequencies ranging from three times in a hundred years to once every four years and a continuous regular sequence of small perturbations. Values of the input parameters (Tables 2-8) are taken from tables of recommended values in Morgan and Finney (I982) and Morgan, Morgan and Finney (I982).

The case with no perturbation is represented by continuous primary rain forest. This provides the reference with which to compare the simulations of the other cases.

The effect of small perturbations of moderate frequency is represented by simulating commercial timber extraction from the rain forest. The first year of this perturbation comprises clearance of the undergrowth, construction of unsurfaced roads and removal of selected trees. The land is then allowed to revert to secondary forest with a dense undergrowth within six years and to primary forest with a sparse undergrowth within sixteen years. Some trees remain on the land immediately after clearance at which time the ground cover is reduced to about I5 per cent. During reversion the ground cover increases to 50 per cent within one year, 80 per cent within two years and over 95 per cent within three years. Tree canopy cover increases to 50 per cent within three years and 75 per cent within four years. The complete cycle is repeated every fifteen years.

A regular cycle of major perturbations of moderate frequency is obtained by simulating clearance of the rain forest for the planting of rubber with the land being cleared and replanted every thirty years. Activities in the year of clearance are concentrated into the two relatively dry periods of the year. The undergrowth is slashed in February and the trees are felled in March. Following the April rainfall peak the land is burned and cleared in May and June. A cover crop is planted in July and young rubber trees are transplanted from the nursery in August. This allows time for the plant cover to become established before the autumn rains. The rubber trees take a further six years to mature before giving a full tree crop cover in the seventh year of the cycle.

Perturbations of moderate magnitude and moderate frequency are associated with clearance of the rain forest for shifting cultivation. Simulations are based on a traditional Malaysian practice as described by Williams-Hunt (I952). One crop per year is obtained with the land being cleared in April and burned in May and the crop being planted in June and harvested in December.

Table 2 Input data for primary tropical rain forest with 8^{o} slope

MS	BD	RD	SD	K	W	RN	SLP	NY
0.26	1.28	0.15	1.00	0.30	0.02	0.20	0.140	100

YEAR	RAIN	RDAY	INTENS	INCEP	ETEO	CFAC
*	*	*	25.0	35.0	0.90	0.002
*	*	*	Repeat values annually to year 100			

Notes: * - data taken from Table 1.
A relatively high value of 0.20 mm/yr is used for the soil renewal rate because all plant residues are returned to the soil.

Table 3 Input data for rain forest with commercial timber extraction every fifteen years on an 8^{o} slope

MS	BD	RD	SD	K	W	RN	SLP	NY
0.26	1.28	0.15	1.00	0.30	0.02	0.20	0.140	100

YEAR	RAIN	RDAY	INTENS	INCEP	ETEO	CFAC
*	*	*	25.0	35.0	0.90	0.002
*	*	*	25.0	25.0	0.90	0.30
*	*	*	25.0	25.0	0.90	0.10
*	*	*	25.0	25.0	0.90	0.04
*	*	*	25.0	30.0	0.90	0.01
*	*	*	25.0	30.0	0.95	0.005
*	*	*	25.0	35.0	1.00	0.001
*	*	*	25.0	35.0	1.00	0.001
*	*	*	25.0	35.0	1.00	0.001
*	*	*	25.0	35.0	1.00	0.001
*	*	*	25.0	35.0	1.00	0.001
*	*	*	25.0	35.0	1.00	0.001
*	*	*	25.0	35.0	1.00	0.001
*	*	*	25.0	35.0	1.00	0.001
*	*	*	25.0	35.0	1.00	0.001
*	*	*	Repeat cycle starting at line 2			

Notes: * - data taken from Table 1.
Values for INCEP and ETEO are interpolated from values given in Morgan, Hatch and Sulaiman (1982); values for CFAC are based on values given in Wischmeier and Smith (1978) for conditions described in the text; soil renewal rate is set at 0.20 mm/yr.

Table 4 Input data for rubber cultivation with replanting every thirty years on an 8° slope

MS	BD	RD	SD	K	W	RN	SLP	NY
0.26	1.28	0.15	1.00	0.30	0.02	0.20	0.140	100

YEAR	RAIN	RDAY	INTENS	INCEP	ETEO	CFAC
*	*	*	25.0	35.0	0.90	0.002
*	*	*	25.0	17.5	0.69	0.33
*	*	*	25.0	25.0	0.90	0.20
*	*	*	25.0	25.0	0.90	0.20
*	*	*	25.0	25.0	0.90	0.20
*	*	*	25.0	25.0	0.90	0.20
*	*	*	25.0	25.0	0.90	0.20
*	*	*	25.0	30.0	0.90	0.20
*	*	*	Repeat above line for 23 years			
*	*	*	25.0	17.1	0.69	0.40
*	*	*	Repeat lines 3 to 31			
*	*	*	Repeat cycle of lines 32 to 61			

Notes: * - data taken from Table 1.

Calculations of INCEP, ETEO and CFAC for first year of clearance are as follows:

(a) INCEP: monthly average of 1 month (Jan) with rain forest (35.0); 3 months (Feb-Apr) of slashed undergrowth and felled trees (25.0); 3 months (May-Jul) of cleared land (0.00); 5 months (Aug-Dec) of ground cover crop and young rubber trees (20.0).

(b) ETEO: monthly average of 1 month (Jan) of rain forest (0.90); 3 months (Feb-Apr) of slashed undergrowth and felled trees but with the residual effects of the previous cover lasting for two months after felling (Morgan, Hatch and Sulaiman, 1982) (0.90); 3 months (May-Jul) of cleared land (0.05); 5 months (Aug-Dec) of ground cover and young trees (0.90).

(c) CFAC: monthly average of 1 month (Jan) of rain forest (0.002); 3 months (Feb-Apr) of slashed undergrowth and felled trees but with residual effects of the previous cover lasting for two months after felling (see above) (0.002); 3 months of bare soil (1.00); 5 months (Aug-Dec) of rubber (0.20).

INCEP values between planting of rubber and its maturity are interpolated; calculations of INCEP, ETEO and CFAC for the first year of subsequent plantings follow the same procedure as above except that for January (INCEP) and January - April (ETEO and CFAC) the values are for the then existing rubber plantation and not for rain forest.

Since the decayed plant matter from a rubber plantation is all returned to the soil, the soil renewal rate is set at 0.20 mm/yr.

Table 5 Input data for shifting cultivation in a sixteen-year cycle on an 8° slope

MS	BD	RD	SD	K	W	RN	SLP	NY
0.26	1.28	0.15	1.00	0.30	0.02	0.19	0.140	100

YEAR	RAIN	RDAY	INTENS	INCEP	ETEO	CFAC
*	*	*	25.0	35.0	0.90	0.002
*	*	*	25.0	20.0	0.60	0.15
*	*	*	25.0	20.0	0.60	0.20
*	*	*	25.0	25.0	0.90	0.10
*	*	*	25.0	30.0	0.90	0.05
*	*	*	25.0	35.0	0.95	0.002
*	*	*	25.0	35.0	0.95	0.002
*	*	*	25.0	35.0	1.00	0.001
*	*	*	Repeat above line for 9 years			
*	*	*	Repeat cycle of lines 2 to 17			

Notes: * - data taken from Table 1.
Values of INCEP, ETEO and CFAC are interpolated from data given in Morgan, Morgan and Finney (1982).
The higher CFAC value in the second year of cropping takes account of a poorer crop cover and reduced structural stability of the soil.
The soil renewal rate is based on an average of 0.10 mm/yr in the cropping years and 0.20 mm/yr in the fallow years.

Table 6 Input data for shifting cultivation in an eleven-year cycle on an 8° slope

MS	BD	RD	SD	K	W	RN	SLP	NY
0.26	1.28	0.15	1.00	0.30	0.02	0.18	0.140	100

YEAR	RAIN	RDAY	INTENS	INCEP	ETEO	CFAC
*	*	*	25.0	35.0	0.90	0.002
*	*	*	25.0	20.0	0.60	0.15
*	*	*	25.0	20.0	0.60	0.20
*	*	*	25.0	25.0	0.90	0.10
*	*	*	25.0	30.0	0.90	0.05
*	*	*	25.0	35.0	0.95	0.002
*	*	*	25.0	35.0	0.95	0.002
*	*	*	25.0	35.0	1.00	0.001
*	*	*	Repeat above line for 4 years			

Table 6 continued

YEAR	RAIN	RDAY	INTENS	INCEP	ETEO	CFAC
*	*	*	Repeat cycle of lines 2 to 12			

Notes: as for Table 5.

Table 7 Input data for shifting cultivation in a four-year cycle on an 8^o slope

MS	BD	RD	SD	K	W	RN	SLP	NY
0.26	1.28	0.15	1.00	0.30	0.02	0.15	0.140	100

YEAR	RAIN	RDAY	INTENS	INCEP	ETEO	CFAC
*	*	*	25.0	35.0	0.90	0.002
*	*	*	25.0	20.0	0.60	0.15
*	*	*	25.0	20.0	0.60	0.20
*	*	*	25.0	25.0	0.90	0.10
*	*	*	25.0	30.0	0.90	0.05
*	*	*	Repeat cycle of lines 2 to 5			

Notes: as for Table 5.

Table 8 Input data for continuous rotational cropping of groundnut, maize and potato on an 8^o slope

MS	BD	RD	SD	K	W	RN	SLP	NY
0.26	1.28	0.15	1.00	0.30	0.02	0.15	0.140	100

YEAR	RAIN	RDAY	INTENS	INCEP	ETEO	CFAC
*	*	*	25.0	25.0	0.87	0.20
*	*	*	25.0	25.0	0.70	0.20
*	*	*	25.0	12.0	0.75	0.30
*	*	*	Repeat cycle of lines 1 to 3			

Notes: * - data taken from Table 1.
Values of INCEP, ETEO and CFAC are taken from Morgan, Morgan and Finney (1982). The soil renewal rate assumes good husbandry practices (Morgan and Finney, 1982).

The land is farmed for two years usually for upland rice and is then allowed to revert to fallow for fourteen years, giving a sixteen year cycle.

The frequency of the shifting cultivation perturbations is increased by shortening the fallow period. This is a common response to increasing population pressure on the land. Simulations are carried out for eleven and four year cycles.

An example of a continuous regular series of small perturbations is the continuous cropping of land in a rotational system. A three-year cycle of groundnut, maize and potato is used to simulate this. Potato was selected because it enabled one crop to be included which would produce conditions with considerably greater potential for erosion than the other crops in the cycle. Good husbandry practice is assumed with the use of fertilizers and the return of crop residues to the soil.

RESULTS AND DISCUSSION

In interpreting the results, the stability of the erosion system is analysed by examining changes in the rooting or top soil depth (RD) over time.

It is doubtful whether, because of their concern with maintenance of the plant assemblage and the use of indicators such as photosynthesis-respiration ratios, the conventional approaches to the assessment of ecosystem stability, as described by Odum(I97I), are directly applicable to erosion systems. Nevertheless, soil development and vegetation evolution are closely linked as recognised by Erhart(I966) in his definitions of biostasy and rhexistasy Biostasy is the condition of increasing soil depth and is associated with the development of an ecosystem to greater diversity and complexity. Rhexistasy is the result of disturbance to the ecosystem and is expressed by a decrease in the soil depth. Strictly, a third condition should exist where the soil depth is unchanging over time. By analogy with the concept of homeostasis in ecosystem studies, it is proposed to call this state homeostasy.

Assigning an erosion system to a particular state of stability or instability requires a definition of a stable state. This state is rather difficult to define precisely in practice, however, but instead of discussing the reasons why this is so and thereby enter an unconstructive debate, it is proposed to adopt a simple working definition and illustrate the problems arising from this as appropriate. Given that the maximum value used in these simulations for the soil renewal rate is 0.20 mm per year, it was decided to describe any system where the change in soil depth was kept within plus or minus 0.20 mm of the starting depth as stable.

Using the above definition and taking the results over the hundred-year period, it can be seen (Table 9) that the majority of the cases simulated are in a state of biostasy with increases in rooting depth ranging from 2.2 mm to 20.0 mm. Four simulations show states of rhexistasy with decreases in soil depth ranging from 3.4 mm to I50.0 mm. The latter occurs twice on the 34^{o} slopes where all the soil is lost within 73 years under shifting cultivation with a four year cycle and within 60 years under continuous cropping. The 8^{o} slope with continuous cropping is the only simulation showing the state of homeostasy. This is not surprising because,as defined in this paper, homeostasy represents a balance between the rate of soil erosion and the rate of top soil renewal and this will only occur on a narrow range of slopes close to the maximum slope at which the agricultural ecosystem can be sustained without excessive erosion.

Table 9 States of the stability of the erosion system under the simulated climatic and landuse conditions

LANDUSE AND TYPE OF PERTURBATION	SLOPES 2^o	4^o	8^o	16^o	34^o
TROPICAL RAIN FOREST	B	B	B	B	B
No perturbations	+20.0	+20.0	+20.0	+19.9	+19.8
COMMERCIAL TIMBER EXTRACTION	B	B	B	B	B
Small magnitude, moderate frequency	+19.8	+19.7	+19.3	+18.6	+17.2
RUBBER CULTIVATION	B	B	B	B	R
High magnitude, moderate frequency	+18.6	+17.2	+14.0	+5.5	-55.9
SHIFTING CULTIVATION (16-YR CYCLE)	B	B	B	B	B
Moderate magnitude and frequency	+18.3	+17.6	+16.2	+13.1	+5.4
SHIFTING CULTIVATION (11-YR CYCLE)	B	B	B	B	R
Moderate magnitude and frequency	+17.1	+16.1	+14.1	+9.4	-3.4
SHIFTING CULTIVATION (4-YR CYCLE)	B	B	B	R	R
Moderate magnitude, high frequency	+12.4	+9.4	+2.2	-26.0	-150.0
CONTINUOUS CROPPING	B	B	H	R	R
Small magnitude, high frequency	+12.1	+8.7	-0.1	-65.2	-150.0

Notes: B = biostasy. R = rhexistasy. H = homeostasy. See text for definitions.
Figures denote change in rooting depth over 100 years in mm.

Table 10 Selected output for the tropical rain forest simulation on an 8^o slope

YEAR	RAIN mm	S/LOSS kg/m^2	CH/RD mm	RD mm	CH/SD mm	SD mm
9	2152	0.0006	0.20	151.8	0.02	1000.2
10	2419	0.0010	0.20	152.0	0.02	1000.2
11	2752	0.0024	0.20	152.2	0.02	1000.2
12	2740	0.0020	0.20	152.4	0.02	1000.2
13	2282	0.0005	0.20	152.6	0.02	1000.3
14	2154	0.0002	0.20	152.8	0.02	1000.3

Notes: S/LOSS = soil loss. CH = change in. RD = rooting depth.
SD = total soil depth.

On gentler slopes, biostasy will prevail and on steeper slopes rhexistasy will occur. For example, from Table 9 it can be deduced that homeostasy will exist for the four-year shifting cultivation cycle on slopes above 8^{0} but less than 16^{0}, with the actual slope being closer to 8^{0} in value. Further simulations covering more slope angles would allow the slope value for stability to be more closely determined.

Cases of biostasy

Biostasy is strictly an example of instability with the soil depth continually increasing. In practice the soil cannot continue to deepen indefinitely because the rate of weathering at the rock-soil interface will decrease as soil depth increases and there will be a maximum depth to that part of the soil which can truly be described as containing the bulk of the root mat. Eventually an equilibrium depth will be reached at which weathering and soil renewal rates equate with the rate of soil erosion. At present the model does not include a routine to allow for this effect.

The response of the erosion system to a disturbance can be measured in terms of the maximum negative or smallest positive change in the rooting depth and in the length of time taken for the rooting depth to return to its initial value. Systems in the state of biostasy register no or relatively small changes in rooting depth and in the latter instances recover before the next disturbance occurs. As examples it can be seen that, using the 8^{0} slope as a reference for comparative purposes and taking the worst response to disturbance within the hundred-year simulation, the tropical rain forest system is immune to the climatic perturbations of a fifty-year return period annual rainfall (Table I0), insensitive to eleven-year cycles of commercial timber extraction (Table II) and somewhat more sensitive to sixteen and eleven-year cycles of shifting cultivation (Tables I2 and I3). In these latter cases rooting depth is reduced by 0.26 and 0.25 mm respectively in the worst year and the system recovers within one to two years. With rubber cultivation the rooting depth is reduced by 0.I2 mm in the worst year and the system again recovers within one year.

Cases of rhexistasy

Rhexistasy is an example of instability where the system enters the spiral of increased erosion which decreases rooting depth, reduces soil moisture storage, produces more runoff and therefore increases erosion still further. Eventually an equilibrium state is reached represented by zero soil and by the erosion of new soil as quickly as it is formed. When approaching and when having reached this stage the simulation becomes somewhat unrealistic because the input parameters continue to represent the crop cover appropriate to the system whereas in fact, as the soil thins the cover will become sparser and less productive until the soil becomes so shallow that plants cannot be supported in it. Thus the final stages of complete top soil removal are likely to occur more rapidly than is suggested by the results of these simulations.

The four-year shifting cultivation cycle on a 34^{0} slope (Table I4) is representative of the rhexistasy condition. The system shows neither a uniform nor an exponential rate of change but instead displays a stepped response. In the early years of simulation rooting depth is reduced by between I and 3 mm over a four-year cycle but between years thirty-eight and forty-five the rate suddenly increases to between 8 and I2 mm. This change in rate is associated with an increase in the number of years when soil loss is detachment-limited until erosion becomes detachment-limited every year. The high rate of decrease in rooting depth is maintained until the top soil disappears, after which the subsoil continues to be removed at an even more rapid rate because the rate of erosion is no longer counteracted by the soil renewal rate but only by the much lower rate of weathering.

Table 11 Selected output for the simulation of commercial timber extraction on an 8° slope

YEAR	RAIN mm	S/LOSS kg/m^2	CH/RD mm	RD mm	CH/SD mm	SD mm	
46	2368	0.0002	0.20	158.9	0.02	1000.6	
47	2512	0.1192	0.11	159.0	-0.07	1000.5	Yr 1 of cycle
48	2440	0.0232	0.18	159.2	0.00	1000.5	
49	2406	0.0191	0.19	159.3	0.01	1000.5	
50	2421	0.0032	0.20	159.5	0.02	1000.5	
51	2348	0.0009	0.20	159.7	0.02	1000.6	

Notes: as for Table 10.

Table 12 Selected output for the simulation of a sixteen-year shifting cultivation cycle on an 8° slope

YEAR	RAIN mm	S/LOSS kg/m^2	CH/RD mm	RD mm	CH/SD mm	SD mm	
17	2214	0.0001	0.19	152.6	0.02	999.7	
18	2323	0.2383	0.00	152.6	-0.17	999.6	Yr 1 of cycle
19	2556	0.5784	-0.26	152.4	-0.43	999.1	Yr 2 of cycle
20	2327	0.0445	0.16	152.5	-0.01	999.1	
21	2033	0.0073	0.18	152.7	0.01	999.1	
22	2547	0.0010	0.19	152.9	0.02	999.1	

Notes: as for Table 10.

Table 13 Selected output for the simulation of an eleven-year shifting cultivation cycle on an 8° slope

YEAR	RAIN mm	S/LOSS kg/m^2	CH/RD mm	RD mm	CH/SD mm	SD mm	
78	2175	0.0001	0.18	161.0	0.02	998.5	
79	2316	0.1201	0.09	161.0	-0.07	998.4	Yr 1 of cycle
80	2662	0.5462	-0.25	160.8	-0.41	998.0	Yr 2 of cycle
81	2178	0.0119	0.17	161.0	0.01	998.0	
82	2257	0.0094	0.17	161.1	0.01	998.0	
83	2297	0.0003	0.18	161.3	0.02	998.0	
84	2230	0.0003	0.18	161.5	0.02	998.1	

Notes: as for Table 10.

Table 14 Selected output for the simulation of a four-year shifting cultivation cycle on a 34° slope

YEAR	RAIN mm	S/LOSS kg/m^2	CH/RD mm	RD mm	CH/SD mm	SD mm	
5	2161	0.0475	0.11	148.2	-0.02	997.6	
6	2479	1.3455	-0.90	147.3	-1.03	996.5	Yr 1 of cycle
7	2305	1.5282	-1.04	146.3	-1.17	995.4	Yr 2 of cycle
8	2163	0.1152	0.06	146.3	-0.07	995.3	
9	2152	0.0839	0.08	146.4	-0.05	995.3	
10	2419	1.4810	-1.01	145.4	-1.14	994.1	Yr 1 of cycle
11	2752	4.2969	-3.21	142.2	-3.34	990.8	Yr 2 of cycle
12	2740	0.6390	-0.35	141.9	-0.48	990.3	
13	2282	0.0808	0.09	142.0	-0.04	990.3	
14	2154	0.5723	-0.30	141.7	-0.43	989.8	Yr 1 of cycle
15	2195	1.4454	-0.98	140.7	-1.11	988.7	Yr 2 of cycle
16	2475	0.2714	-0.06	140.6	-0.19	988.5	
17	2214	0.0791	0.09	140.7	-0.04	988.5	
36	2520	0.9715	-0.61	122.7	-0.74	968.0	
37	2669	1.0112	-0.64	122.1	-0.77	967.3	
38	2362	3.3864	-2.50	119.6	-2.63	964.7	Yr 1 of cycle
39	2222	4.5483	-3.40	116.2	-3.53	961.1	Yr 2 of cycle
40	2110	0.4298	-0.19	116.0	-0.32	960.8	
41	2389	0.3579	-0.13	115.9	-0.26	960.5	
42	2313	4.0843	-3.04	112.8	-3.17	957.4	Yr 1 of cycle
43	2386	6.3483*	-4.81	108.0	-4.94	952.4	Yr 2 of cycle
44	2477	1.5560	-1.07	107.0	-1.20	951.2	
45	2483	0.9312	-0.58	106.4	-0.71	950.5	
46	2368	6.3004*	-4.77	101.6	-4.90	945.6	Yr 1 of cycle
47	2512	6.6836*	-5.07	96.5	-5.20	940.4	Yr 2 of cycle
48	2440	2.3114	-1.66	94.9	-1.79	938.6	
49	2406	1.9267	-1.36	93.5	-1.49	937.2	
65	2473	3.9908*	-2.97	32.0	-3.10	873.6	
66	2430	6.4654*	-4.90	27.1	-5.03	868.5	Yr 1 of cycle
67	2365	6.2924*	-4.77	22.3	-4.90	863.6	Yr 2 of cycle
68	2744	5.6859*	-4.29	18.0	-4.42	859.2	
69	2106	3.3986*	-2.51	15.5	-2.64	856.6	
70	2420	6.4388*	-4.88	10.7	-5.01	851.6	Yr 1 of cycle
71	2184	5.8109*	-4.39	6.3	-4.52	847.0	Yr 2 of cycle
72	2371	4.9130*	-3.69	2.6	-3.82	843.2	
73	2305	3.7197*	-2.58	0.0	-2.89	840.3	
74	2356	6.2685*	0.00	0.0	-4.88	835.5	Yr 1 of cycle
75	2216	5.8960*	0.00	0.0	-4.59	830.9	Yr 2 of cycle

Notes: * = detachment-limited erosion rate.
Other details as for Table 10.

The continuous cropping system on the 34^{o} slope follows a similar pattern with the stepped increase occuring between years thirty-one to thirty-six.

On the 16^{o} slope continuous cropping produces relatively small changes in rooting depth in the early years of simulation ranging from +0.1 to -1.0 mm over a three-year cycle. Between years forty-nine and fifty-four the rate changes to -0.5 to -2.7 mm and between years eighty-five to ninety increases again to over -4.0 mm. In year one-hundred the soil loss becomes detachment-limited for the first time. Overall,the pattern of this simulation is similar to the others showing rhexistasy but is responding more slowly. Another case showing a relatively slow response is the four-year shifting cultivation cycle on the 16^{o} slope which in the early years of simulation includes six cycles out of nine where the system recovers its rooting depth before the next cycle begins. In the next fifteen cycles recovery takes place only in two of them. Overall the soil loss reduction remains relatively uniform at about 0.9 mm over each four-year cycle except that in the last cycle simulated the loss increased to 1.51 mm. A longer period of simulation would determine whether this represents the first stepped increase in the rate of rooting depth reduction.

With rubber cultivation on the 34^{o} slope, the system is never able to recover before the onset of disturbance caused by the next replanting. The least unstable response occurs in the first thirty-year cycle where rooting depth is reduced by a maximum of 0.87 mm in the year of land clearance and planting. In subsequent years the trend is towards further but smaller reductions in rooting depth because the frequency and magnitude of negative changes in depth outweigh those of the positive changes. The overall reduction at the end of the first thirty-year cycle is 4.3 mm. Reductions in the second and third cycles are 7.2 mm and 20.2 mm respectively. The change in rate in the third cycle corresponds to the stepped response observed in the other cases of rhexistasy. Further evidence of the rapidly deteriorating condition is provided by the occurrences of detachment-limited erosion in years ninety-two, ninety-eight and one-hundred.

Cases of homeostasy and near homeostasy

Five cases from Table 10 were identified for further examination where the change in rooting depth over the hundred-year period of simulation was 6.0 mm or less. Two of these revealed cases of biostasy but with a relatively slow accumulation of top soil. With rubber cultivation on a 16^{o} slope the maximum disturbance occurred in year ninety-two when replanting coincided with a high rainfall total. Rooting depth was reduced by 0.67 mm but this was recovered within six years. With the sixteen-year shifting cultivation cycle on the 34^{o} slope recovery of the rooting depth following two years of cropping occurs within five to sixteen years.

The continuous cropping regime on the 8^{o} slope is, as pointed out earlier in a state of homeostasy overall. It also retains this state within thirty-one of the thirty-three cropping cycles. The greatest reductions occur in the rooting depth in the years when potatoes are grown but unless these coincide with high rainfall totals, they are less than 0.2 mm and recovery takes place in the following year. The system is not quite resilient to the fifty-year return period rainfall events of years eleven and twelve (Table 15) where the rooting depth is reduced by 0.31 mm in year eleven and 0.33 mm in year twelve. The depth never recovers to the value of 150.2 mm of years eight to eleven but instead tends to stabilise for a long period at about 149.7 mm. Recovery is nearly complete by years ninety-seven to one-hundred, by which time the depth has slowly increased to 149.9 mm.

Table 15 Selected output for the simulation of continuous rotational cropping on an 8° slope

YEAR	RAIN mm	S/LOSS kg/m^2	CH/RD mm	RD mm	CH/SD mm	SD mm	
9	2152	0.2003	-0.01	150.2	-0.14	999.0	Potatoes
10	2419	0.1262	0.05	150.2	-0.08	998.9	Groundnut
11	2752	0.5826	-0.31	149.9	-0.44	998.5	Maize
12	2740	0.6120	-0.33	149.6	-0.46	998.0	Potatoes
13	2282	0.0614	0.10	149.7	-0.03	998.0	Groundnut
14	2154	0.0770	0.09	149.8	-0.04	998.0	Maize
15	2195	0.1843	0.01	149.8	-0.12	997.8	Potatoes
16	2475	0.0971	0.07	149.9	-0.06	997.8	Groundnut
17	2214	0.1238	0.05	149.9	-0.08	997.7	Maize
18	2323	0.2601	-0.05	149.9	-0.18	997.5	Potatoes
19	2556	0.2024	-0.01	149.8	-0.14	997.4	Groundnut
20	2327	0.2384	-0.04	149.8	-0.17	997.2	Maize
21	2033	0.1026	0.07	149.9	-0.06	997.2	Potatoes
22	2547	0.1574	0.03	149.9	-0.10	997.1	Groundnut
23	2205	0.0879	0.08	150.0	-0.05	997.0	Maize

Notes: as for Table 10.

It could be argued that this condition of homeostasy is the ideal one to aim for because agricultural use can be sustained without excessive erosion. In practice, however, it represents the marginal case and perhaps only requires slightly greater perturbations than those simulated here to trigger off a change of state towards rhexistasy. Such an event might occur with a series of crop failures due to the action of pests and disease, leading to a doubling of the CFAC values and a lowering of the soil renewal rate. Thus in a sense homeostasy represents a condition of potential instability since the agricultural ecosystem can only sustain its soil resource through consistent and careful management.

An example of a condition close to homeostasy but tending towards biostasy is provided by the four-year shifting cultivation cycle on the 8° slope where the rooting depth always recovers within two to four years except in the years ten to thirteen when the rainfall is high. In year eleven the rooting depth is reduced by 0.56 mm whereas the next highest reduction is 0.35 mm in year nineteen. Over successive four-year cycles rooting depth generally increases by 0.I to 0.3 mm.

The eleven-year shifting cultivation cycle on a 34° slope represents a condition close to homeostasy but tending towards rhexistasy. This simulation shows considerable fluctuation where rooting depth changes over the eleven-year cycles range from +I.2 mm in years thirteen to twenty-three to -I.I mm in years seventy-eight to seventy-nine. This last cycle lies between cycles where the rooting depth increased by I.I mm and 0.3 mm (Table I6). Although the change in rooting depth over the hundred years is relatively small, the fluctuations in the system indicate that it is potentially unstable. A further disturbance in any of the years following the peak reduction in rooting depth could trigger a state where recovery never occurs. At present the rooting depth is recovered within two to nine years in seven out of the nine cycles simulated.

Table 16 Selected output for the simulation of an eleven-year shifting cultivation cycle on a 34° slope

YEAR	RAIN mm	S/LOSS kg/m^2	CH/RD mm	RD mm	CH/SD mm	SD mm	
64	2603	0.0031	0.18	148.6	0.02	988.4	
65	2473	0.0019	0.18	148.8	0.02	988.4	
66	2430	0.0015	0.18	149.0	0.02	988.4	
67	2365	0.0021	0.18	149.2	0.02	988.5	
68	2744	2.1982	-1.54	147.6	-1.70	986.8	Yr 1 of cycle
69	2106	0.7160	-0.38	147.3	-0.54	986.2	Yr 2 of cycle
70	2420	0.1758	0.04	147.3	-0.12	986.1	
71	2184	0.0681	0.13	147.4	-0.03	986.1	
72	2371	0.0027	0.18	147.6	0.02	986.1	
73	2305	0.0022	0.18	147.8	0.02	986.1	
74	2356	0.0009	0.18	148.0	0.02	986.1	
75	2216	0.0005	0.18	148.1	0.02	986.1	
76	2395	0.0013	0.18	148.3	0.02	986.2	
77	2082	0.0004	0.18	148.5	0.02	986.2	
78	2175	0.0008	0.18	148.7	0.02	986.2	
79	2316	0.8094	-0.45	148.2	-0.61	985.6	Yr 1 of cycle
80	2662	3.4921	-2.55	145.7	-2.71	982.9	Yr 2 of cycle
81	2178	0.1073	0.10	145.8	-0.06	982.8	
82	2257	0.0818	0.12	145.9	-0.04	982.8	
83	2297	0.0024	0.18	146.1	0.02	982.8	
84	2230	0.0025	0.18	146.3	0.02	982.8	
85	2483	0.0017	0.18	146.4	0.02	982.8	
86	2391	0.0019	0.18	146.6	0.02	982.9	
87	2377	0.0011	0.18	146.8	0.02	982.9	
88	2132	0.0008	0.18	147.0	0.02	982.9	
89	2499	0.0022	0.18	147.1	0.02	982.9	
90	2367	1.3347	-0.86	146.3	-1.02	981.9	Yr 1 of cycle
91	2265	1.5320	-1.02	145.3	-1.18	980.7	Yr 2 of cycle
92	2633	0.3531	-0.10	145.2	-0.26	980.5	
93	2021	0.0297	0.16	145.3	-0.00	980.5	
94	2356	0.0025	0.18	145.5	0.02	980.5	
95	2554	0.0045	0.18	145.7	0.02	980.5	
96	2087	0.0005	0.18	145.9	0.02	980.5	
97	2128	0.0005	0.18	146.0	0.02	980.5	

Notes: as for Table 10.

CONCLUSIONS

The simulations are designed to show that the model can be used to determine the state of erosional stability, as expressed by changes in rooting or top soil depth, for agricultural ecosystems. The results indicate that it is possible to recognise three broad conditions of biostasy, rhexistasy and homeostasy and that, for the latter, detailed examination of the output file from the model can reveal the extent to which the system is potentially unstable. For the states of biostasy and homeostasy information is obtained on the peak response, either maximum negative or smallest positive change in rooting depth, resulting from any disturbance and the length of the period required for recovery. In the cases of rhexistasy, the simulations showed that the rate of rooting depth reduction increased in a stepped pattern rather than following a continuously increasing trend. The onset of detachment-limited erosion rates was symptomatic of the start of the phase of complete top soil removal.

Compared with the kinds of responses of ecosystems to disturbances discussed by Trudgill(I977) those identified here are relatively simple. This is because the model is so constructed as to always operate with positive feedback.

According to the results of these simulations, the tropical rain forest environment is resilient to small and moderate sized perturbations of moderate frequency but is less resilient to major perturbations of moderate frequency (rubber cultivation) and to moderate perturbations of high frequency (shifting cultivation with a four-year cycle), especially on the steeper slopes. Least resilience is shown to the continuous disturbances of small magnitude created by continuous cropping.

Although an attempt was made to make the simulations and therefore these results as realistic as possible no discussion is presented of their realism. The user of the model is free to adjust the input parameter values if it is felt that more realistic results would thereby be obtained. The results presented here show how the model can be used to compare the effects of different agricultural ecosystems on the maintenance of soil depth. It should be stressed that the model is very sensitive to a one per cent change in the annual rainfall total and sensitive to a similar magnitude change in rooting depth. Thus if the simulations had been carried out for a rainfall sequence with a mean value of 2500 mm and an initial rooting depth of 0.I0 mm, the results would have been quite different and states of rhexistasy would have been observed more frequently.

The objective of this research programme has been to produce a model which provides a reasonable representation of the soil erosion system, is reasonably efficient in terms of ease of data input requirements and computational manipulation and time, is valid over a wide range of conditions where erosion is likely to be a problem and which allows a relatively rapid but realistic assessment of erosional stability for agricultural ecosystems over thirty to one hundred year periods. Future users of the model must judge for themselves the extent to which the results have been successful.

REFERENCES

Carson, M.A. and Kirkby, M.J. 1972. Hillslope form and process. Cambridge University Press.

Chia, L.S. 1968. An analysis of rainfall patterns in Selangor. Journal of Tropical Geography, 27, 1-18.

Chia, L.S. 1973. Reliability of West Malaysian rainfall records: an objective evaluation. Journal of Tropical Geography, 36, 1-7.

Douglas, I. 1969. The efficiency of humid tropical denudation systems. Transactions, Institute of British Geographers, 46, 1-16.

Erhart, H. 1966. Bio-rhexistasie, biostasies évolutives, hetérostasie. Importance de ces notions en gitologie minère exogène. Comptes-Rendues, Acad. Sci. Paris, Series D.263, 1048-1051.

Morgan, R.P.C. and Finney, H.J. 1982. Stability of agricultural ecosystems: validation of a simple model for soil erosion assessment. International Institute for Applied Systems Analysis Collaborative Paper No. CP-82-76.

Morgan, R.P.C., Hatch, T. and Sulaiman, W. 1982. A simple procedure for assessing soil erosion risk: a case study for Malaysia. Zeitschrift für Geomorphologie Supplementband 44, 69-89.

Morgan, R.P.C., Morgan, D.D.V. and Finney, H.J. 1982. Stability of agricultural ecosystems: documentation of a simple model for soil erosion assessment. International Institute for Applied Systems Analysis Collaborative Paper No. CP-82-59.

Odum, E.P. 1971. Fundamentals of ecology. Saunders, Philadelphia.

Ollier, C.D. 1975. Weathering. Longman.

Trudgill, S.T. 1977. Soil and vegetation systems. Clarendon, Oxford.

University of Agriculture, Malaysia. 1979. Joint soil research project UPM-Belgium. Annual Report. Volume 1: Sub-project Soil Physics. Faculty of Agriculture.

Williams-Hunt, P.D.R. 1952. An introduction to Malayan aborigines. Kuala Lumpur.

Wischmeier, W.H. and Smith, D.D. 1978. Predicting rainfall erosion losses. A guide to conservation planning. USDA Agricultural Handbook No. 537.