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Soil Erosion Models and Implications for Conservation of Sloping Tropical Lands

*C.W. Rose**

ABSTRACT

A catena of modeling approaches are briefly reviewed including dynamic stochastic and deterministic approaches. It is shown that a dynamic stochastic description of soil erosion, with appropriate parameter identification, can be identified with a deterministic description of processes, but these descriptions are mutually helpful. The role of such dynamic process models is reviewed, but more attention is given to simpler limited-parameter models and their use in extensive multi-country field studies in Southeast Asia and Australia. Extensive hydrologic data collected on runoff could be adequately interpreted using a single-parameter model of infiltration reflecting the dominant dependence of infiltration rate on rainfall rate. Data on soil and water loss from bare-plot treatments were interpreted to yield a single soil erodibility parameter at each site. The effectiveness of a variety of soil conservation options appropriate to the humid tropics was evaluated, and process studies drawn upon to seek generalization of this evaluation. The issues of model prediction of soil and water loss are also briefly considered.

INTRODUCTION

Research on soil erosion and soil conservation is assisted by the use of a variety of models, which differ in their context, purpose, and degree of detail. This paper briefly reviews a selected range of model types, with different objectives, but focuses on parameter-efficient types of models and their application in extensive collaborative multi-country field studies.

These field studies of soil erosion and soil-conservation alternatives were carried out in Southeast Asia and Australia. A common experimental methodology and method of data interpretation was employed in these studies in humid tropical sloping lands. The implications of process studies in evaluating the effectiveness of various soil-conservation measures, and the issue of soil and water loss prediction in tropical steep lands are also briefly considered.

Dynamic stochastic *versus* deterministic description of soil erosion

A feature of research in the last decade has been the demonstrated utility of examining processes from both a stochastic and deterministic viewpoint. The processes of soil erosion have commonly been described deterministically, a differential equation being established by considering mass conservation of water and sediment in a fundamental interval, with mathematical descriptions of the rate processes believed to be involved in adding or subtracting sediment to the water layer in the element. Whilst there have been differences in concepts concerning process representation, this is the general approach used by Foster (1982) and developed by Hairsine and Rose (1991, 1992a, b) for example. Fig. 1 illustrates the deterministic model of rainfall-driven erosion used by Hairsine and Rose (1991).

However, Lisle et al. (1998) give a general stochastic description of the erosion process, considering the motion of a soil particle or aggregate either to be at rest on the soil bed or moving in the water layer flowing over the bed, the transition between these two states being assumed to be random in nature. The periods spent by a particular particle at rest or in motion can then be described by initiation and deposition-rate parameters.

This theory, developed by Lisle et al. (1998), has shown that the stochastic description of the movement of rocks and other bedload components in rivers given by H. Einstein (1937) is in fact a special case of this more general description. Einstein neglected the time period spent by a particle in motion compared to the dwell time, a quite reasonable assumption in the river bedload context. However, in soil erosion, the time spent by a particle in motion can be shown not to be negligible compared to dwell time (Lisle et al., 1997). The stochastic description is thus characterised as transport mediated by exchange between a mobile phase and a stationary phase. Fig. 2 illustrates, for particular values of the initiation and deposition-rate parameters, features of the spatial and temporal density dependence of particles either in motion or at rest.

Lisle et al. (1998) go on to show that by giving specific identity to the parameters of the stochastic theory, the resulting two partial differential equations can be identified with the deterministic description of Hairsine and Rose (1991). The first differential equation deals with sediment in the mobile phase, the second with sediment in the deposited layer or immobile phase (Fig. 1).

That an equivalent outcome is achieved by such conceptually quite different approaches to soil erosion description can be regarded as either comforting or not surprising. The stochastic description allows an interpretation of experiments using tracer methods, which could provide a quite different test of model predictions, which is not available from a deterministic modeling approach.

Dynamic and steady-state models of erosion processes

It is well known that even in experiments in which a constant rainfall and runoff rate is imposed on a soil bed in a flume, both sediment concentration and its settling-velocity characteristics change with time. Numerical solution of

*C.W. Rose, Faculty of Environmental Sciences, Griffith University, Queensland 4111, Australia. *Corresponding author: C.Rose@mailbox.gu.edu.au

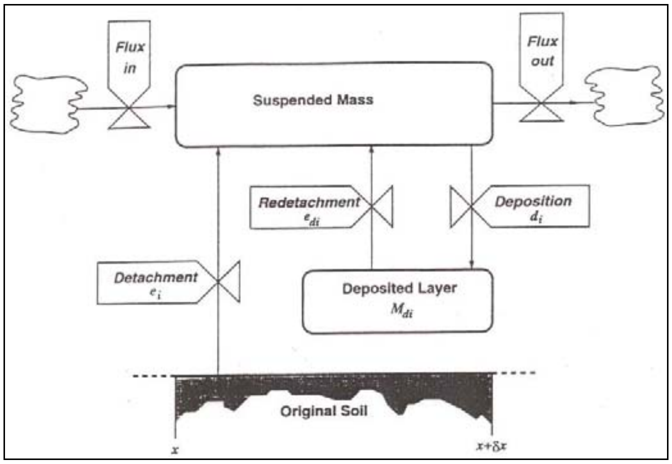

Figure 1. Forrester-style flow diagram illustrating the interaction of erosion processes between the sediment flux, the original soil, and the deposited layer formed from previously eroded soil. Rate of rainfall detachment e_i, redetachment e_{di}, and deposition d_i for size class i are shown as valve symbols (after Hairsine and Rose, 1991).

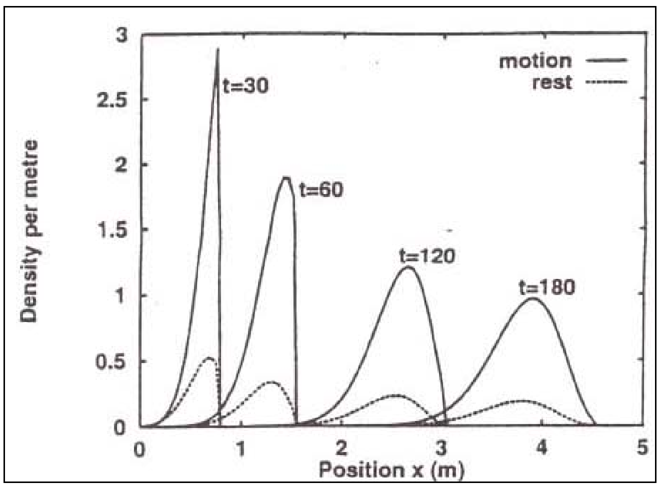

Figure 2. The evolution of the probability density of location of a single eroding soil particle initially at x = 0. This spatial density for the particle either in motion (————), or at rest (-------), is shown for four times, t (seconds). The initiation and deposition-rate parameters have particular values, and a velocity of overland flow of 0.025 m s^{-1} is assumed. The distribution is skewed at short times, and approaches a Gaussian distribution at long times (after Lisle et al.**, 1998).**

dynamic models of erosion processes, which include recognition of the spatial and temporal variation in both these characteristics of sediment, is very demanding (Rose and Hogarth, 1998). However, by making simplifying assumptions, Sander et al. (1996) show that a simple approximate analytical solution of the dynamic equations describing rainfall-driven erosion can be reached which allows description of the features of controlled experiments. Fig. 3 illustrates how well this approximate solution can describe the measured time variation in sediment concentration when parameters defined in the theory are obtained by fitting the theory to the data. Results from a range

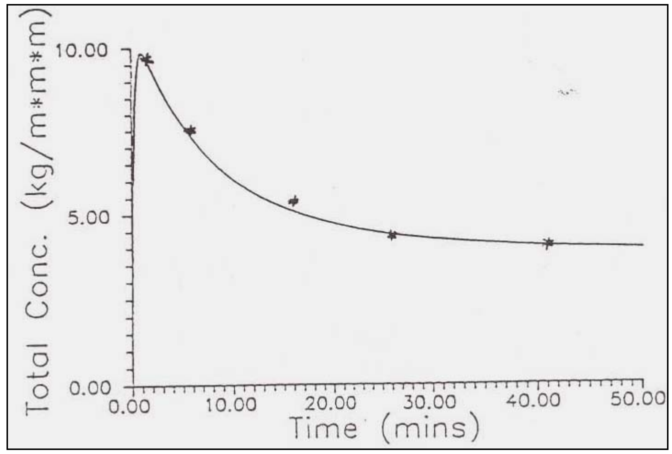

Figure 3. Sediment concentration for a slightly disperse sandy clay loam (classified as an Aridisol and solanchak) shown as a function of time when measured at the end of a 5.8 m long flume at low slope subject to rainfall of rate 100 mm h^{-1} and drop size 2.3 mm, water depth being 10 mm. The asterisks are experimental values from Proffitt et al. (1991) and the solid line the approximate analytical solution of Sander et al. **(1996) (after Rose and Hogarth, 1998).**

of experiments, for example with different water depths, give some confidence in the physical realism of the parameters involved. Work is progressing on the ability of such theory to correctly predict measured change through time in the settling-velocity characteristics of eroded sediment. Success in this area could be of assistance in interpreting significant variation in the enrichment of chemicals bound to eroded soil (Palis et al., 1990). The comparison of dynamic models with data from controlled experiments is useful in testing the validity of process description employed. However, in extensive field studies of soil erosion, use of fully dynamic erosion theory is onerous, and simplification based on steady-state assumptions, but with dynamic description of the hydrology, is more feasible. The remainder of this paper outlines an example of such a simplified methodology applied in multi-country studies of soil erosion and conservation.

Experimental methods

Data referred to in this paper was collected at two sites in the Philippines and Australia, and one site each in Thailand and Malaysia.

The experimental investigations were carried out at the scale of farmer practice at the chosen sites by measuring soil loss and runoff rate from hydrologically isolated runoff plots. At the plot exit, coarser or "bed-load" sediment was deposited and separated from finer "suspended load" sediment, which has more potential for off-site effects. Since erosion depends on flow rate, this was measured at the plot exit, using tipping-bucket devices on plots of up to about 600 m^2 area, and flumes for larger plots. Measurement equipment, data-logging and data-conversion techniques are described in Ciesiolka et al. (1998a), Ciesiolka and Rose (1998b), and Coughlan and Rose (1997).

Reference plots at all sites studied included one in which the crop of major interest was cultivated and grown using current farmer methods, and also a plot in which soil was cultivated using farmer methods but kept bare. Results obtained from the bare plot were interpreted to yield a soil erodibility parameter, β (Rose, 1993).

Hydrologic methodology

The excess of rainfall over infiltration rate is the dominant source of overland flow in these experiments. Infiltration rate has been dominantly interpreted in terms of one-dimensional models. However, evidence is emerging that the effect of spatial variation in infiltration rate may play the dominant role, at least at the plot scale, in controlling rate change in excess rainfall (Yu et al., 1997a).

At all the study sites, apparent infiltration rate for the plot as a whole was found to follow closely changes in the rainfall rate, and not to be strongly influenced by cumulative infiltration as might be expected from any classical point infiltration theory, for example the Green-Ampt equation. Interpreting this general finding as indicating strong spatial variation in infiltration rate I, Yu et al. (1997a) have shown that the infiltration component of runoff can be well expressed for all sites studied in terms of a one-parameter model. The meaning of this parameter, I_m, is the mean infiltration rate for the plot as a whole if the entire plot was contributing to runoff. Because runoff generation is commonly only from a partial area of the plot, I_m can be described as a mean maximum infiltration rate for the entire plot. The model structure is:

$$I = I_m (1 - \exp(-P/I_m)) \qquad (1)$$

where P is rainfall rate. This is found to represent adequately the observed variation in I with P.

In addition to this descriptor of infiltration rate, two other parameters are required to characterize the relation between rainfall and runoff (Yu et al., 1997b). Firstly, an initial amount of infiltration, F_0, occurs prior to production of any runoff. Secondly, the rainfall excess, P - I, must be routed to the plot outlet. Using the kinematic flow approximation, this involves a lag parameter, α, which depends on factors such as slope, slope length and surface roughness, as well as the time interval of rate measurement.

Once the three parameters, I_m, F_0 and α have been determined, the small-scale runoff-routing model (SSRRM) allows prediction of runoff rate per unit area, Q, as a function of time based on measured rainfall rate, P, as illustrated in Fig. 4.

Soil erodibility methodology

While there is a role for experimentation and modeling designed to test understanding of erosion processes (e.g. Rose and Hogarth, 1998), seeking to represent explicitly all processes of importance is not only challenging but also demanding of information that may commonly be lacking. Thus, for the multi-country field studies reported in this paper, a simpler option was chosen within the program GUEST (Griffith University Erosion System Template) (Misra and Rose, 1990, 1995, 1996) which is based on the theory of Hairsine and Rose (1991, 1992a, b). This simpler option assumes overland flow to be the major source of soil erosion, although the value of the soil erodibility parameter, β, obtained by analysis of experimental data, incorporates the contribution to erosion made by whatever processes are active. Thus, the erodibility β is a composite factor, like the K-factor in the Universal Soil Loss Equation, but in situations where erosion is dominantly flow-driven, the value of β is directly related to the energy required to entrain a unit mass of soil. The GUEST model uses a theoretically (rather than an experimentally) derived expression for the upper limit to sediment concentration, called the transport limit or capacity by Foster (1982). For sheet flow, Hairsine and Rose (1992a, b) show that

$$c_t = \frac{F\sigma SV}{\phi(\sigma/\rho - 1)}, \qquad (2)$$

where F is the fraction of stream power of overland flow used in erosion (≈ 0.1), σ and ρ are wet sediment and water density respectively, S the land slope, V flow velocity, and φ the "deposit ability" of sediment (the mean settling velocity of sediments), measured as described by Lisle et al. (1996).

Using Manning's equation and assuming turbulent kinematic flow, Ciesiolka et al. (1995) show that it follows from Equation 2 that the mean sediment concentration in an erosion event, $\bar{c}_t$, can be written as

$$\bar{c}_t = k\ Q_e^{0.4}, \qquad (3)$$

where k is approximately constant (Yu et al., 1997b), and where Q_e is an effective value for the event of the runoff rate per unit area, Q, given by

$$Q_e = \left(\frac{\Sigma Q^{1.4}}{\Sigma Q}\right)^{2.5}, \qquad (4)$$

where ΣQ is total event runoff.

The erodibility, β, of soil in a plot from which eroded sediment has a mean sediment concentration of $\bar{c}$ is then defined by

$$\bar{c} = \bar{c}_t^{\beta}. \qquad (5)$$

Unless $\bar{c}$ is enhanced by other than flow-driven process, β ≤ 1, and β is reduced by increases in soil strength (Misra and Rose, 1995). The total mass of soil lost during an erosion event, M, given by $\bar{c}$ ΣQ, follows from Equations (3), (4) and (5) as:

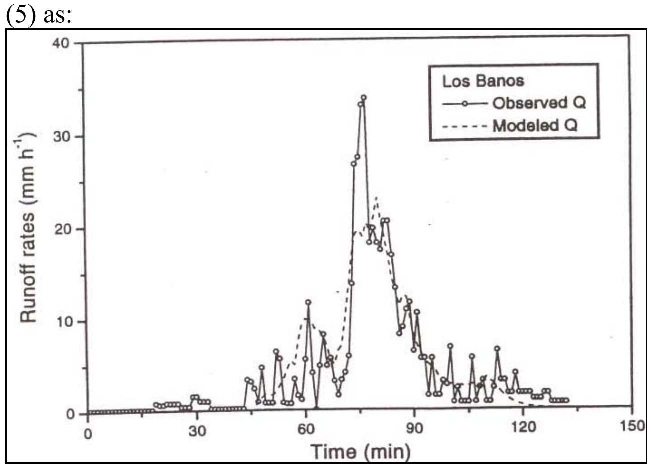

Figure 4. A comparison of runoff rate measured at the Los Banos, Philippine site with tipping-bucket technology and runoff rate modeled as described in the text (after Yu et al., 1997a).

$$M = k^{\beta}\ Q_e^{0.4\beta}\ \Sigma Q. \quad (6)$$

The value of k depends on surface roughness, slope, slope length, and also on rill geometry and frequency, a factor ignored in Equation (2). Fentie et al. (1997) gave an experimentally supported development of Equation (2), which interprets the effect of rills on sediment concentration and soil loss. Fig. 5 gives a particular illustration of this general theory, showing that, except for very narrow rectangular rills, rills do lead to increased sediment concentration as expected.

Review of Results of Multi-Country Soil-Conservation Experiments

This section reviews some of the major experimental outcomes, more detail being given by Coughlan and Rose (1997) and Soil Technology (1995).

Total soil and water loss

Table 1 summarizes average annual runoff, the runoff coefficient, soil loss and average sediment concentration for five sites. Data is given first for the bare weeded plot, followed by farmer practice and an "improved practice". Soil information is included in the table.

Soil losses from the bare-plot treatment exceeded 100 t/ha/y, except at Nan, Thailand, where drought conditions saw little runoff, and at VISCA, the Philippines, where runoff was low due to very permeable soil. Table 1 shows that soil losses were still unacceptably high with conventional farmer practice. The nature of the improved practices varied, but they reduced soil loss to less than 20 t ha^{-1} y^{-1} at Kemaman, Malaysia, and less than 10 t ha^{-1} y^{-1} at other sites.

All improved practices were "agronomic" in nature and did not include terracing (Rose et al., 1997b). The use of biomass to provide "surface contact cover" was very effective in reducing soil loss. This type of cover is in sufficiently intimate contact with the soil surface to impede overland flow, and is thus not easy to quantify accurately. Like the "canopy cover" provided by the crop canopy, surface contact cover intercepts raindrops, but its proximity to the soil provides important additional benefits which include a more consistent soil environment, probably important to soil biota.

The great effectiveness of surface contact cover in reducing soil loss is shown by comparing results for the two treatments other than the bare plot at the Kemaman site (Table 1). The canopy cover provided by cocoa and its companion shade trees was similar for both treatments. Soil loss from the treatment with the tree canopy but no living ground cover was less than from the bare soil, but only by a factor of 1.4; in contrast, the improved practice using a living grass-legume surface cover reduced average annual soil loss by a factor of over seven.

Permanent leguminous hedgerows were employed as the improved practice at both the Los Banos and VISCA sites in the Philippines, with hedgerow trimmings providing a mulch component for the alley crop. Table 1 shows that the reduction in soil loss is greater than would be expected from the reduction in runoff. Whilst hedgerows can fail with dramatic effects under extreme typhoons, they appear to encourage both net deposition of sediment and infiltration of water.

Where the farmer practice included up and down slope cultivation, total runoff was little less than from bare soil, or even greater at the VISCA site, where land cultivation for weed enhanced infiltration. Table 1 also shows the runoff coefficient, R_c, to be highly variable, particularly between sites. Interestingly, the range in R_c for lighter texture soils (0.27 to control on the bare plot produced large aggregates and 0.62) is higher than the range for clay soils (0.02 to 0.19) (Table 1). Thus sandy soils are not always more permeable, the higher permeability of the clay soils presumably being associated with better water-stable aggregation, and probably higher biotic activity.

The improved practices had a larger effect on sediment concentration than on runoff with soils of light texture (e.g. at Goomboorian in Australia), but elsewhere the relative effect

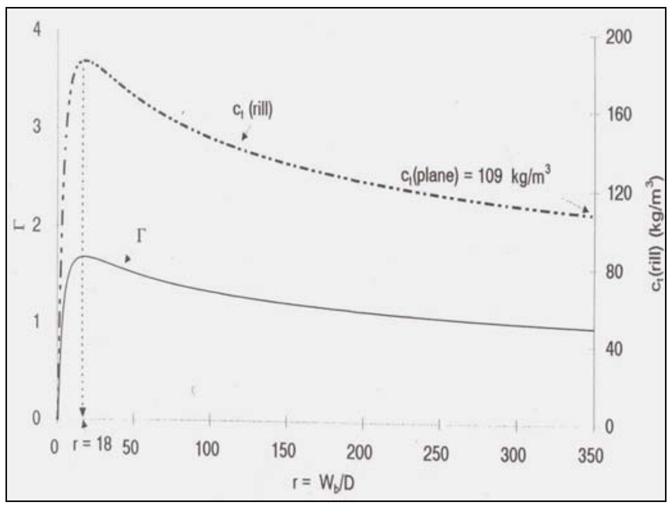

Figure 5. This figure refers to a particular erosion scenario of slope, slope length and roughness, soil characteristics and spacing of rectangular rills described in Fentie et al. (1997). The upper curve shows how c_t varies with the ratio, r, of rill width W_b to water depth D, becoming essentially equal to the value of c_t with plane or sheet flow when r becomes large. The ratio Γ on the left-hand scale is the ratio c_t (rill) to c_t (plane), Γ having a maximum value for r = 18 in this scenario, and tending to unity as r increases (after Fentie et al., 1997).

Table 1. Average annual runoff, runoff coefficient, soil loss and sediment concentration from plots at five experimental sites.

Site*	Treatments (soil type)	Average Annual Runoff (mm)	Runoff** Co-efficient	Soil Loss (t ha)	Sediment Concentration (kg m^3)
Kemaman, Malaysia 4.5 years Sandy clay loam 17% slope Average annual rainfall = 3638 mm	Bare plot (Orthoxic Tropudult) No living ground cover Grass and legume ground cover	2245 1287 413	0.62 0.35 0.11	127 90 17	5.7 7.0 4.1
Nan, Thailand 1 year Clay Average slope ≈ 30% Annual rainfall 1993 = 1886 mm	Bare plot (Oxic Paleustult) Clean cultivation farmers practice Tephrosia hedgerows	42 10 10	0.02 < 0.01 < 0.01	7.2 0.6 0.4	17.1 6.0 4.0
Los Banos, the Philippines 6 years Clay Average slope = 18% Average annual rainfall = 2037 mm	Bare plot (Typic Tropudalf) Clean cultivated farmers practice Alley cropping and mulching	393 387 114	0.19 0.19 0.06	184 119 6	47 31 5.3
VISCA, the Philippines 2 years Clay 50% slope plots Average annual rainfall = 2800 mm	Bare plot (Oxic Dystropept) Clean cultivated furrows up-and-down slope Alley cropping and mulching	55 84 16	0.02 0.03 < 0.01	69 38 3	125 45 19
Goomboorian, Gympie, Australia 3 years Loamy sand Slope: Landslope = 14% Furrow slope = < 6% Average annual rainfall = 1045 mm	Bare plot (Typic Eutropept) Conventional plot, no surface contact cover Improved practice - furrow mulching	286 213 150	0.27 0.20 0.14	216 51 3	76 24 2

*Information on length of experimental period, soil type, slope, and average annual rainfall over the experimental period is given.
**Runoff coefficient, Rc = average annual runoff/average annual rainfall

varied. The "suspended load", consisting of the finer fraction of eroded sediment, was highest for the Kemaman and Goomboorian sites, and was commonly enriched in nutrients (Hashim et al., 1995, 1997). Though surface contact cover greatly reduces soil loss, it increases the fraction of the soil lost as suspended load, and thus typically increases sediment enrichment (Palis et al., 1990).

Soil erodibility and nutrient loss

The erodibility, β, defined in Equation (5) was found to vary with soil type, cultivation, time since last cultivation, and the method of weed control. Factors such as soil strength, soil consolidation effects, and change in soil surface characteristics could be among more basic soil characteristics, which affect the value of β.

Change in erodibility with time unaffected by subsequent cultivation was seen most clearly at the Goomboorian site, since weeds were controlled chemically. Over the three-year period of experimentation, β initially had values fluctuating from 1.1 to 1.0, finally settling at a value of about 1, with some minor fluctuation possibly due to pulsing of sediment through the 36 meter-long ridge/furrow system (Rose et al., 1997a). Since furrow slope was only about 5%, the reason for β being greater than 1.0 initially could be due to a rainfall-driven contribution to sediment concentration.

At both Philippine sites (Los Banos and VISCA), soils were clay in texture and the value of β fluctuated more than for the loamy sand at the Goomboorian site, apparently due to soil weakening associated with cultivation used for weed control.

At the Los Banos site, the mean value of β resulting from 40 measurements over a period of three years was 0.86 with a standard deviation of 0.19. Thus the mean value was less than for the sandy Goomboorian soil, but variation in β was greater, apparently due to the periodic cultivation. The bare site at Kemaman was not cultivated, the mean value of β being 0.31 with a standard deviation of 0.11 and little evidence of a time trend in the 48 measurements over four years. Rose et al. (1997a) give more detail.

For soils of lighter texture (e.g. Goomboorian), high enrichment ratios led to higher than expected values of nutrient loss. Especially if fertilizer applications are substantial, as was the case for pineapple production at Goomboorian, nutrient loss in soluble form can also be important, and even dominant for nitrogen (Hashim et al., 1997). With clay soils and limited fertilizer application, as at Los Banos and VISCA in the Philippines, there is little enrichment and the relationship between soil and nutrient loss is rather direct.

Process study implications for soil conservation measures in tropical steep lands

Neglecting effects such as landslides (Bruijnzeel, 1990) and soil displacement by cultivation (e.g. Govers et al., 1994; Turkelboom et al., 1997), and focusing on erosion driven by overland flow and rainfall, the data reviewed in the previous section illustrate and emphasize the great importance of ground-hugging surface contact cover in reducing soil and water loss. Such cover reduces the shear stress borne by the soil, not only by direct protection from rainfall impact, but by reducing the velocity of overland flow (and thus c_t, Equation (2)), by sharing much of the shear stress due to overland flow, and by inhibiting rill development.

Though continuous maintenance of perhaps at least 30% surface contact cover appears to provide adequate protection against water erosion, in general there are at least some periods during the cultivation cycle when this is not feasible or suitable, making some extra soil-conserving support system desirable or essential. In the humid tropics, this extra form of protection is often provided, perhaps inadvertently, by the typically small plot size, so that the down slope distance available to overland flow is restricted by some form of vegetation barrier, such as the leguminous hedgerows in the Philippine sites. Such "agronomic" ways of breaking up long slope lengths are commonly better adapted to the contextual constraints on farmers in the humid tropics than are graded terraces typically used in larger scale mechanized agriculture. There are many alternatives to leguminous hedgerows available to the farmer (Kemper et al., 1992; Hoey, 1997), and process studies give supporting reasons for their general effectiveness.

DISCUSSION OF PREDICTION

Data from the field study sites demonstrate the highly variable and episodic nature of both runoff and soil loss, indicating the risk in using short-term monitoring as a guide to long-term behavior. One reason for model development is that once the hydrologic and erodibility parameters in such models have been determined at a site, the same conceptual framework can be used to make longer term predictions of soil and water loss, assuming at least longer term rainfall data has been collected or can be synthesized.

The same conceptual and computing framework as in the GUEST-analysis technology (Yu et al., 1997b) can be used in a predictive mode, using the program GUEPS (Griffith University Erosion Prediction System) (Yu and Rose, 1997). The flow chart of GUEPS is shown in Fig. 6.

GUEPS recognizes that runoff rate is not commonly measured in erosion studies. As shown in Fig. 6, where, as is common, runoff amount but not runoff rate is measured, program GOSH (Generation of Synthetic Hydrograph) (Yu et al., 1998) can be used to predict runoff rates, thus enabling GUEPS to be used.

However, if runoff has not been measured, but rainfall rates are available or can be synthesized, then the model SSRRM can be used to generate runoff rate, provided its three parameters are known or can be inferred.

Whilst conventional testing of the predictive ability of GUEPS has been carried out by dividing data into separate sets for parameter evaluation and predictive testing, such testing, though desirable, still avoids the major general impediment to prediction, which is the complete lack of model parameter values. The ability of the USA to overcome this limitation for its application of the USLE (Wischmeier and Smith, 1978), RUSLE (Renard et al., 1991) and the WEPP (Foster and Lane, 1987) soil-erosion technologies must be acknowledged and applauded.

One of the driving motivations in the general move toward more process-related types of models has been the hope that the parameters introduced into them do bear some relationship, however approximate, to real characteristics, including soil characteristics. Recognizing the limitations in such relationships, Misra and Rose (1995) found that soil strength, readily measurable in situ, affected sediment concentration in a manner consistent with the GUEST methodology. Also, soil erodibility, β, has been found to relate in an expected way to the yet more fundamental characteristics of mechanical analysis (Yu et al., 1999).

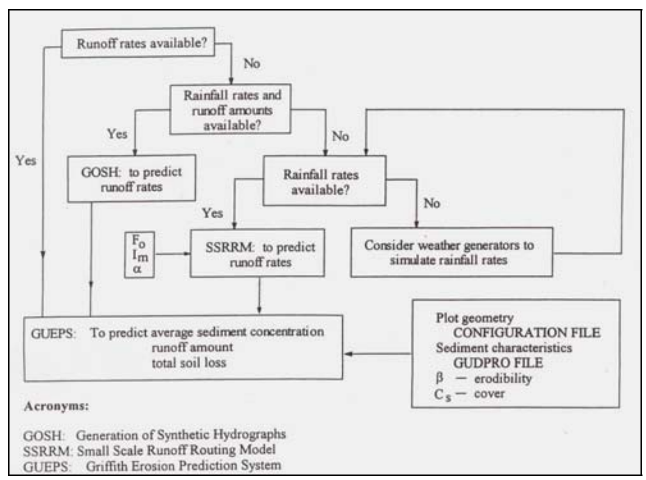

Figure 6. Flow chart for event soil loss and runoff prediction using GUEPS methodology (after Rose and Yu, 1998).

CONCLUSIONS

It is suggested that either stochastic or deterministic dynamic models of soil erosion, especially when combined with controlled experimentation, provide the opportunity to test the adequacy of alternative models designed to describe in some detail the processes at work in rainfall or flow-driven soil erosion. Lessons learnt from such studies are a source of guidance in selecting simpler parameter-efficient models for use in extensive field studies or in a predictive context.

The extensive data collected in the reported field studies has expanded experience in model parameter values and in testing predictive models of soil and water loss. The data has also allowed evaluation of a number of soil conservation methodologies, which have met with farmer acceptance in some areas by comparing the soil and water loss with that from common farmer practice and from bare soil.

Three soil conservation practices have been shown to be feasible and adaptable to sloping-land agriculture in the humid tropics. These are:

1. With agricultural crops, seek to maintain at least about 30% surface contact cover at times when runoff-inducing rainfall can occur.
2. Break up land with long hillslopes devoted to agricultural crops into short segments (e.g. of length say 10-15 m) with strips of more permanent vegetation. These strips should be approximately on the contour (achievable with low-technology aids), but these strips can be of any desired vegetation or vegetation combination, and need not be extensive if they provide a significant resistance to overland flow.
3. With tree crops (as at the Kemaman site), surface contact cover should also be sought, though such cover should not be allowed to compete too strongly with the tree crop, especially during tree establishment.

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