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Soil erosion modelling with EUROSEM at Embori and Mukogodo catchments, Kenya

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Abstract

The applicability of the European Soil Erosion Model (EUROSEM) in Kenya was tested on two subcatchments: Embori, which lies within a large-scale commercial wheat- and barley-growing region on the slopes of Mt Kenya; and Mukogodo, a dry rangeland region used for communal grazing, which lies at lower altitudes. For both catchments, EUROSEM was used to simulate interrill erosion from single storm events on plots of 10 m by 2 m. The model was calibrated and validated for a barley crop at Embori and three treatments of bare, grass and shrub covers at Mukogodo. The results indicated that EUROSEM was applicable to the Embori catchment, as correlation coefficients of 0·91 and 0·84 were obtained between observed and simulated runoff and soil loss, respectively. However, for Mukogodo, the model did not adequately predict soil loss from vegetated plots having grass or shrubs, although it could predict runoff from bare plots and grass quite well ($R^2 = 0{\cdot}97$, $R^2 = 0{\cdot}60$, respectively) as well as soil loss from bare plots ($R^2 = 0{\cdot}58$), but the standard errors of estimate at 4·67 mm were rather high ($P = 0{\cdot}95$). Thus, EUROSEM requires improvements in terms of being able to predict runoff and soil loss in semi-arid regions of Kenya, so that it can accommodate multiple vegetation covers, rangeland conditions and soils with surface sealing properties. In addition, the model requires further testing to sample a wider range of climatic and land use types for it to be applicable to Kenya and rangeland conditions generally. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords: EUROSEM; erosion; modelling; runoff; soil erosion; barley; bare; grass; rangelands; Embori; Mukogodo; Kenya

Introduction

There are many models capable of simulating various aspects of soil erosion phenomena. Models can assist in the understanding of the system and therefore when used for hypothesis testing, can provide a predictive tool for management (Beven, 1989). The choice of which model to use depends on the objective, scale, availability of data and support facilities. If the purpose is to predict the long-term amounts of erosion under alternative management practices, then empirical models such as the USLE (Wischmeier and Smith, 1978) and GAMES (Madramootoo *et al*., 1988) are adequate. For more detailed analysis, including understanding the processes of erosion, physically based models (Flanagan *et al*., 1991; Nearing, 1998; Zhang *et al*., 1996; Brazier *et al*., 2000) such as AGNPS (Young *et al*., 1989) and EUROSEM (Morgan *et al*., 1998a) can be used.

The European Soil Erosion Model (EUROSEM) is a dynamic distributed (process-based) model designed to simulate the erosion, transport and deposition of sediment over the land surface by interrill and rill processes (Morgan *et al*., 1998a). The model can be applied to individual storm events and to spatial scales ranging from small fields to small catchments. It is designed particularly to predict soil loss from those storms that contribute most of the annual soil loss and therefore have return periods of six months or more. EUROSEM has explicit simulation of interrill and rill flow; plant cover effects on interception and rainfall energy; rock fragments or stoniness effects on infiltration, flow velocity and splash erosion; and changes in the shape and size of rill channels as a result of erosion and deposition.

EUROSEM can be applied to smooth slope planes without rills, rilled surfaces and surfaces with furrows. The dynamic nature of the simulation provides advantages over approximate flow methods commonly used (Morgan *et al*., 1998b). Application of EUROSEM to catchments requires that the watershed be divided into a network of homogenous slope planes and channel elements, which are arranged in a cascading sequence to enable correct routing of water and sediments over the land surface (Morgan *et al*., 1998a). The outputs from EUROSEM include total runoff, total soil loss, storm hydrograph and storm sedigraph for each slope element simulated. By interpreting the model outputs, it is possible to determine the timing of peak runoff, sediment delivery to the watercourses and the sediment sinks.

EUROSEM has been validated for the UK (Quinton, 1994), the Netherlands (Folly *et al*., 1999), Spain (Albaledejo *et al*., 1994) and the C5 Watershed in Oklahoma, USA (Quinton and Morgan, 1998). In these tests, the model was found to simulate quite well the time to peak discharge, the peak discharge and the overall shape of the hydrograph, but it tended to overestimate sediment concentrations. Veihe *et al.* (2001) also tested EUROSEM in Costa Rica, Nicaragua and Mexico and found that there were also problems with the model's inability to take into consideration crusting. Moreover, modelling of grasslands was problematic as discussed later in this paper. Quinton (1997) demonstrated that uncertainty bounds, due to parameter uncertainty, were wide for applications to plot data from the UK. Although EUROSEM has been applied to European conditions quite successfully, its applicability to rangeland conditions has not been thoroughly tested. When applied to Central America, the model predicted yearly runoff and soil loss quite well but was unable to simulate runoff and erosion in single events because of its inability to model crusting (Veihe *et al*., 2001). Trials of the runoff component of EUROSEM in Nigeria (Audu *et al*., 2004) showed that the model could simulate the results of rainfall simulator trials carried out on bare soil surfaces well. However, to date no attempt has been made to evaluate EUROSEM against erosion data from natural runoff plots in Africa. This paper therefore presents an evaluation of EUROSEM using plot data from two different catchments, Embori and Mukogodo, in Kenya, aimed at determining the applicability of the model to the prevailing topography, soils, climate and land use conditions. Particular attention is given to the ability of the model to deal with different crop and vegetation covers.

Characteristics of the Embori and Mukogodo Catchments

The Embori catchment is a region on the slopes of Mt Kenya, located around 0·04° north and 37·31° east, where mechanized large-scale cereal farming is practised. Although the catchment lies at altitudes of 2000–2800 m above sea level, it is situated on the leeward side of the mountain and receives a mean annual rainfall of 735 mm, but the seasonal distribution is such that the amounts are insufficient for proper crop growth (Gichuki *et al*., 1998). However, the relatively cool temperatures allow the growing of wheat and barley, but the farmers sometimes practise water conservation techniques such as stubble mulch tillage and minimum tillage. The soils are loams classified as humic Andosols (FAO taxonomy) (Sombroek *et al*., 1980). Soil erosion is not evident except in the areas affected by mass wasting. However, plot studies at Embori have recorded soil erosion rates reaching 102 t ha^{-1} in seasons with heavy rainfall (Mati, 1999).

The Mukogodo catchment is located around 0·38° north and 37·07° east, at lower altitudes north of the Embori catchment. Although the area is semi-arid, altitudes are high at 1750 m above sea level. The area is hot and dry, receiving on average 362 mm of rain per annum (Berger, 1989; Thomas and Liniger, 1994; Liniger *et al*., 1998). The soils are sandy loams, classified as chromic Luvisols, developed on basement system rock (Sombroek *et al*., 1980). The predominant vegetation is shrubland. Land use is mainly communal grazing of livestock (cattle, sheep, goats) by pastoral communities, but wildlife also share the grazing lands without any formal management. The land is denuded, recording vegetation covers less than 40 per cent with evidence of soil erosion in the form of interrill, rill and even gullies on the steeper slopes. However, soil erosion rates of 35 t ha^{-1} have been recorded; this is lower than at Embori because, although the land has very poor cover, extensive compaction and surface sealing properties of the surface soils have resulted in high runoff rates but lower soil loss amounts (Mati, 1999).

Model Parameterization

Field data on surface runoff and soil loss for model calibration and validation were collected from runoff plots at both Embori and Mukogodo, providing ten years of data for diverse dates between 1984 and 1994 (NRM^3 1997). Each site was equipped with a weather station, which included a recording rain gauge. All the plots are identical, each measuring 10 m long by 2 m wide and having a collector tank of 0·2 m^3 for the inner tank and 1·15 m^3 for the outer tank. Runoff and sediment sampling were done manually.

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The main characteristics of Embori and Mukogodo catchments are summarised in Table I. In both catchments, climatic, crop phenology and soil loss data were obtained from the NRM^3 (Natural Resources Monitoring, Modelling and Management) database at Nanyuki. The runoff and soil loss data were collected from the runoff plots, with three replications, for the period 1994–96. The available data could only permit the simulation of EUROSEM as a single slope-plane catchment model, to predict interrill erosion. The model was tested against a total of four treatments. One treatment was of a barley crop at Embori, while the other three treatments were at Mukogodo and comprised bare (naturally bare land from overgrazing), perennial grass and shrub (*Acacia mellifera*).

The rainstorms for each catchment can be divided into four types: single peak; multiple peaks but with the highest at the beginning of the storm; multiple peaks with the highest in the middle of the storm; and multiple peaks with the highest at the end of the storm. Half of the data were used for calibration and the other half for validation of the model, taking care to ensure that high, medium and low values of each storm type were included in both data sets. This was to cover the possibility that calibration parameters would vary seasonally with storm type, since calibrated input parameter values derived for the start of the main rains would only be applicable to storms also occurring at that time. This type of sample splitting was used by Klemes (1986) as the first level of a hierarchical scheme for model testing. In total, ten storm events were obtained for Embori and 12 for Mukogodo in each group.

EUROSEM requires input data from several sources. Some of these data were obtained from erosion plot studies and other field measurements, while the parameters for the remaining factors were estimated using guide tables (Morgan *et al*., 1998a). For instance, crop cover (COV) was obtained from records, surface roughness (RFR) was measured with a straight rule and tape, and the soil cohesion (COH) was measured with a torvane on bare land, but it had to be estimated for cropland. Since hydrograph and sedigraph data were not available, calibration and validation of the model could be undertaken only for total runoff and soil loss from each storm.

Calibration of EUROSEM

Trial runs of EUROSEM were first made using the measurable parameters (Table I). This helped to obtain input values for parameters which had been identified as sensitive in previous studies (Quinton, 1994; Veihe and Quinton, 2000; Veihe *et al*., 2000). These include the effective net capillary drive (G), maximum volumetric moisture content of the

Table I. Basic EUROSEM input parameters

Parameter	Embori	Mukogodo
Measured data		
Slope (%)	13	5
Soil texture	Loam	Loamy sand
Cohesion (bare land)	2·0	2·8
D50	300	350
Porosity (calculated)	0·31	0·419
Soil depth (m)	2·0	1·26
Roughness (bare land)	4·0	0·5
Rock cover (%)	0	0
Soil detachability	2·0	3·0
Effective capillary drive (mm)	375	147
Volumetric moisture content	0·10–0·23	0·10–0·34
Estimated from guide tables		
DINTR	–	–
EROD	2·0	3·0
FMIN	1·8	1·7
G	375	147
IRMANN	0·3	0·01
PANGLE	–	–
PLANTH	–	–
SHAPE	–	–
THMAX	0·25	0·38

A dash represents parameters which vary from day to day on the plot.

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soil (THMAX) and detachability of the soil (EROD). To determine the optimum values of saturated hydraulic conductivity (FMIN), COH and Manning's roughness coefficient for interrill area (IRMANN), the model was first simulated for several values of FMIN until it yielded runoff equivalent to observed amounts for a particular event. Then the best value of FMIN would be used in further simulations with different values of IRMANN and COH until predicted soil loss was nearly equivalent to observed values. Dynamic parameters such as infiltration recession factor (RECS), cohesion of the soil (COH), maximum interception storage (DINTR), initial volumetric moisture content (THI), and percentage basal area of vegetation (PBASE) were thereafter determined by running the model several times (trial and error) until their optimal values were achieved. This was when simulated runoff and soil loss were as close to observed values as possible.

Model Validation

EUROSEM was used to make simulations with baseline parameters, while some adjustments were made in the values of COH, DINTR, IRMANN, COV, PBASE and THI according to the prevailing catchment conditions for each event, obtaining the values of simulated runoff and soil loss shown in Tables II and III. These were used in a linear regression between observed and simulated runoff and soil loss respectively (Figures 1, 2, 3, 4 and 5). The fit of the

Table II. Validation of EUROSEM for barley crop at Embori catchment

			Surface runoff (mm)		**Soil loss (t ha^{-1})**	
Date	**Rainfall (mm)**	**Cover (%)**	**Observed**	**Simulated**	**Observed**	**Simulated**
15/05/94	8·6	8	5·49	1·45	0·99	0·34
16/05/94	18·9	9	12·90	7·92	4·95	2·85
18/05/94	8·7	12	4·58	2·89	0·69	0·74
22/05/94	36·7	18	21·03	14·37	3·95	4·10
09/06/94	21·8	37	5·83	5·77	2·62	2·69
23/06/94	19·0	25	2·20	1·89	0·68	0·43
02/07/94	4·9	42	1·68	0·00	0·48	0·00
07/11/94	23·6	65	1·92	0·00	0·03	0·00
12/07/96	14·9	10	1·47	2·40	0·45	0·54
16/07/96	20·3	13	10·91	5·52	2·16	1·60

Table III. Validation of EUROSEM for Mukogodo catchment

		Bare plots					**Grass plots**			
		Runoff (mm)		**Soil loss (t ha^{-1})**			**Runoff**		**Soil loss (t ha^{-1})**	
Date	**Rainfall (mm)**	**Observed**	**Simulated**	**Observed**	**Simulated**	**Cover (%)**	**Observed**	**Simulated**	**Observed**	**Simulated**
05/05/94	15·6	10·8	10·2	4·5	2·4	7	9·5	11·2	2·4	0·8
16/05/94	16·7	9·6	9·1	1·1	1·7	9	7·0	9·4	1·1	1·4
18/08/94	9·6	5·3	3·7	1·3	0·6	9	2·8	3·5	0·3	0·5
03/10/94	9·4	1·9	0·5	0·5	0·0	6	0·3	0·3	0·0	0·0
11/11/94	11·1	7·7	2·1	1·5	0·1	21	6·6	1·6	1·0	0·0
08/02/95	34·5	18·5	16·9	3·0	4·4	26	11·7	22·5	1·3	3·6
13/02/95	8·8	4·3	3·4	1·0	0·6	28	3·2	3·1	0·6	0·4
02/03/95	35·2	23·0	18·6	4·2	3·1	11	20·6	12·9	2·5	1·4
10/05/95	9·8	5·1	3·7	1·1	0·4	41	2·4	3·4	0·5	0·4
14/07/95	7·0	2·8	1·2	0·3	0·1	20	0·3	0·9	0·0	0·1
04/09/95	13·7	7·1	3·0	1·4	0·4	22	1·8	2·5	0·4	0·2
19/09/95	10·5	5·6	0·0	1·8	0·0	24	1·4	0·0	1·0	0·0

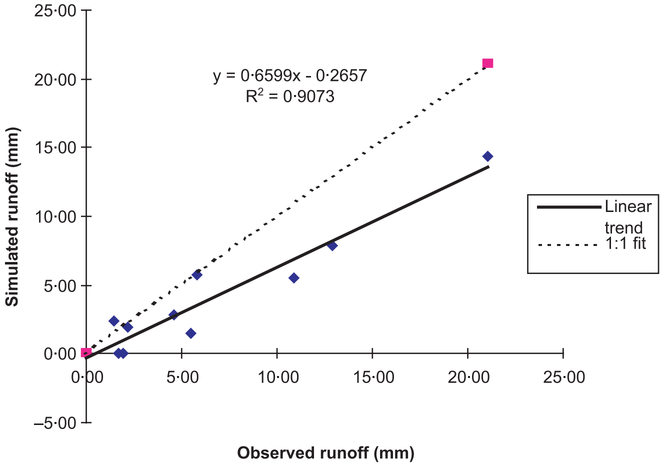

Figure 1. Linear regression between observed and simulated runoff from barley plots at Embori.

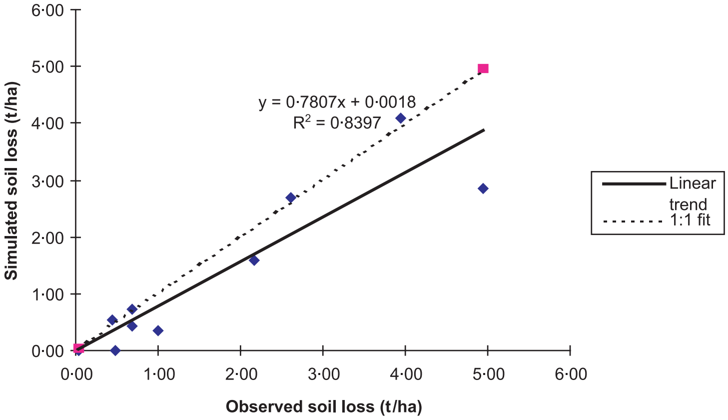

Figure 2. Linear regression between observed and simulated soil loss from barley plots at Embori.

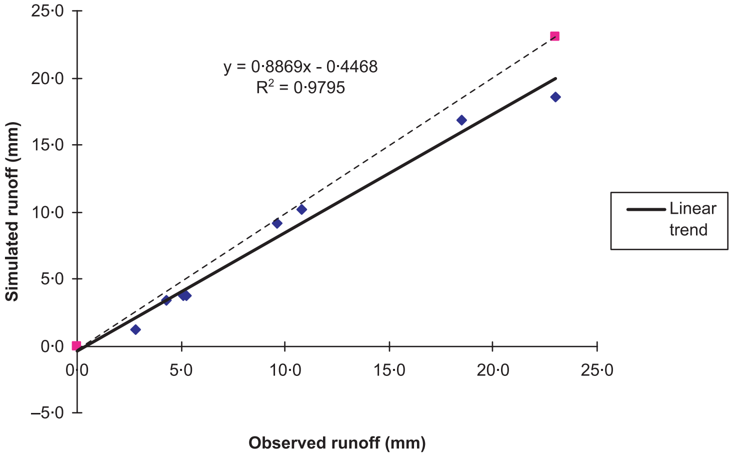

Figure 3. Linear regression between observed and simulated runoff from bare plots at Mukogodo.

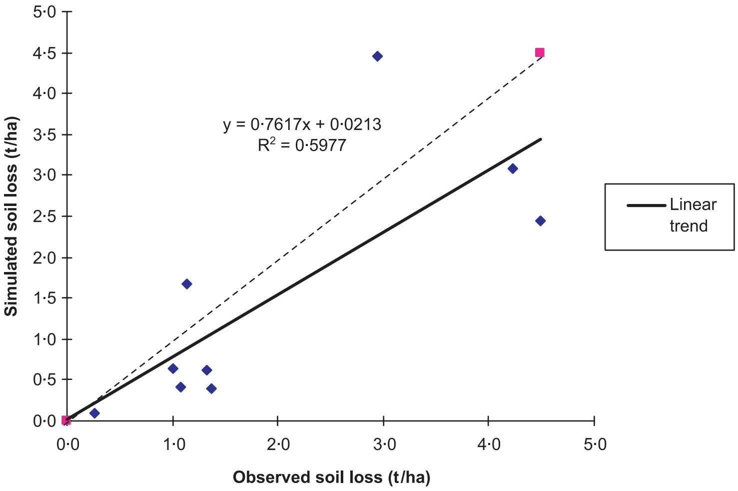

Figure 4. Linear regression between observed and simulated soil loss from bare plots at Mukogodo.

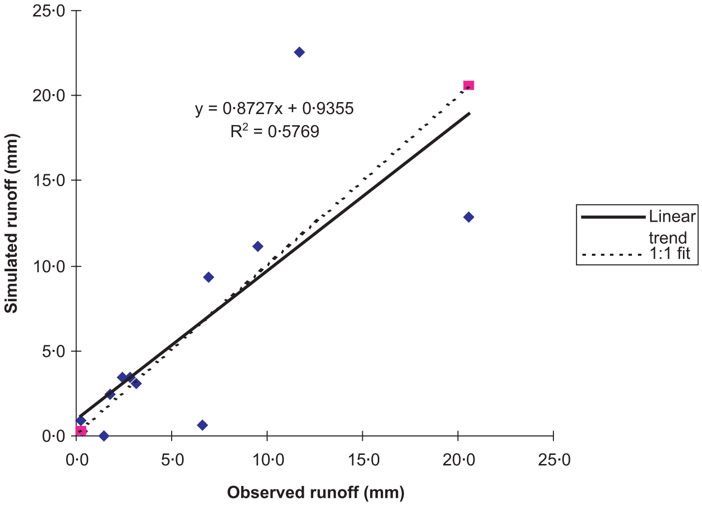

Figure 5. Linear regression between observed and simulated runoff from grass plots at Mukogodo.

45° line (ASCE, 1996) showed that both runoff and soil loss were underpredicted by the model in all the treatments, while a goodness-of-fit test obtained a good fit for soil loss at Embori (5 per cent), but a poor fit for the other treatments. In addition, high standard errors of estimate were obtained in all the treatments.

These results showed that EUROSEM predicted soil loss under barley at Embori catchment quite well, obtaining correlation coefficients of 0·91 and 0·84 for runoff and soil loss, respectively. For Mukogodo, the model obtained correlation coefficients of 0·97 and 0·60 for runoff and soil loss, respectively, from bare plots. However, it failed to predict soil loss in both grass and shrub plots, but predicted runoff from grass plots quite well, obtaining a correlation coefficient of 0·58, although the standard error of 4·67 mm was rather high ($P = 0{\cdot}95$).

Discussion

The validation of EUROSEM showed that the model could predict runoff and soil loss for Embori catchment quite well (Figures 1 and 2), obtaining good correlation coefficients under a barley crop. The gradients of the regression line indicated that both runoff and soil loss were underpredicted. By comparison, EUROSEM has been found to overpredict soil loss in England (Quinton, 1994) and in the Netherlands (Folly *et al*., 1998), while in Costa Rica the values varied greatly (Veihe *et al*., 2001). The opposite results obtained under the semi-arid conditions can be attributed to several factors, including differences in climate, soils, land use and management. For instance, the rainfall characteristics are quite different in the rangeland regions, where rainstorms have bigger drop sizes (Lal, 1976) capable of higher rates of splash erosion. This would lead to higher erosion rates than those predicted by the detachment component of EUROSEM.

It is worth noting that the crop, topography, land preparation and cultural practices in the Embori catchment have similarities with the European conditions under which EUROSEM was developed. At Embori, tillage is fully mechanized, the crop is barley, and the climate is cool with relatively low rainfall intensities as compared to other parts of Kenya. But the type of agro-ecological zone and management at Embori represent less than 10 per cent of the total land area of Kenya. Notwithstanding, the results obtained for Embori should be interpreted with caution because of the number of uncertainties associated with some of the model parameters used in the simulation. For instance, the values of FMIN, COH, THI, THMAX, IRRMAN and PBASE, which are sensitive to model performance, were estimated or calibrated in this study. According to Quinton (1994) simulation results can be subject to considerable uncertainty as a result of difficulties in model parameterization. This could be attributed to the lack of routines in EUROSEM to model saturated overland flow and crusting, and the fact that it is difficult to simulate the hierarchical nature of erosion processes and the dynamic nature of many of the parameters used in the model, as was the case in this study.

The poor performance of EUROSEM in Mukogodo catchment puts to question the applicability of the model in the region. Whereas the model could predict runoff from bare and grass plots as well as soil loss from bare plots quite well (Figures 3, 4 and 5) it did not predict soil loss under either grass or shrub covers. Several factors could have resulted in this poor performance in Mukogodo. Among them are the physical and climatic factors, which are quite different from those of Embori. In Mukogodo, storms having as little as 4 mm of rainfall with intensities of 3 mm h^{-1} have recorded runoff on bare plots (Mati, 1999). In addition, the soils of Mukogodo are prone to surface sealing (Mainga and Mbuvi, 1994) and are therefore likely to produce more runoff, since saturated hydraulic conductivity is achieved over the top few millimetres of the soil quite rapidly. It would therefore be necessary for future model improvements to include adjustments for conditions where soil crusting is widespread. This was also found to be a major problem in Central America (Veihe *et al*., 2001).

The fact that the model failed to predict soil loss under vegetation in Mukogodo suggests that there are effects of vegetation variables in the erosion process that may not be explained by the routines used by EUROSEM. EUROSEM assumes that vegetation is evenly distributed across a computational element and that the effects of the vegetation can be spatially averaged. For an arable crop where the plants are evenly distributed, such as the barley grown at Embori, this assumption probably holds. However, in the rangelands of Mukogodo the vegetation is patchy and mixed. This gives rise to two problems. First, the spatial averaging of the effects of vegetation on soil erosion and runoff generation fall down. Where vegetation is patchy, runoff tends to be generated between patches and flows around them. Flow paths tend to be convoluted and erosion rates are higher in the bare areas than in the patches where the vegetation occurs. In these situations it is the spatial arrangement of the vegetation that controls the erosion: vegetative barriers trap sediment while bare areas encourage sediment detachment and transport. Modelling highly spatially variable sediment production rates with a set of parameters reflecting the average conditions is therefore unlikely to be successful. The second problem is the description of vegetation within EUROSEM: the EUROSEM guide tables do not separate between grasses and forbs, yet the latter are quite prevalent in Mukogodo. The phenology of the tree covers simulated by EUROSEM may not be comparable to the shrubs found in the catchment. This highlights the difficulties of explicitly modelling rangeland conditions and suggests that EUROSEM may not be suited to simulating erosion dynamics under rangeland conditions.

Other features of rangelands are also difficult to capture in a process-based model such as EUROSEM. In particular we know little about how animals compact the soil, their effect on aggregate stability, soil hydraulic properties and soil strength, nor how these properties change once the animals have moved on. In some cases grazing may have taken place over many years leading to compound effects which we also do not understand.

EUROSEM needs high resolution data on rainfall, soil hydrology, detailed surface geometry, soil mechanical properties and vegetation characteristics (Quinton and Morgan, 1998), which was limited in the current study. According to Quinton (1997), one of the major difficulties faced by those wishing to use predictions from physically based models is the level of uncertainty surrounding the model output, including various types of errors. Nearing (2000) suggests that erosion models should be expected to predict erosion only as well as the replicate in a plot experiment. This suggests that while EUROSEM predicted soil erosion from rangelands poorly, it did perform at a similar level to a physical model and should perhaps not be judged too harshly.

Impacts of vegetation cover on soil loss

EUROSEM was simulated for the Embori catchment using hypothetical covers of barley, maize, grass and forest, respectively. The model predicted an exponential decay of soil loss with increase in cover in all four simulations (Figure 6). The trends of the curves showed that high erosion rates were predicted from the maize and barley crops as compared to grass and forest. The curves for the maize crop indicated that soil loss drastically drops from 4·5 t ha^{-1} on bare ground to about 1·0 t ha^{-1} at 100 per cent cover. Morgan (1996) observed that for maize cover, in its early stages of growth, canopy is close to the ground and the slope of the curve is relatively steep. At higher canopy covers, a linear relationship with lower slope is obtained.

The grass and forest covers were predicted to control soil erosion completely at 70 per cent vegetation cover, while for the cultivated crops, maize and barley, there was little change in soil loss with increase in cover after 70 per cent. The exponential decline of soil loss with increasing cover was predicted for maize, but with a higher exponent value than for barley. Steeper exponents were obtained for grass and forest, indicating the rapid decrease in soil loss with cover. These results are typical of soil loss under vegetation covers obtained by other researchers (Elwell and Stocking, 1976; Morgan, 1996). The exponents of the curves are close to those obtained in many studies (Elwell, 1978; Brown *et al*., 1989). The results obtained in this study indicate that natural vegetation such as grass and forest are the optimum covers for controlling soil erosion in the catchment.

Conclusions

EUROSEM was found to be applicable for predicting both runoff and soil loss for the Embori catchment, recording correlation coefficients of 0·91 and 0·84, respectively, between observed and simulated values. For Mukogodo, the model obtained good correlation coefficients for runoff from bare plots ($R^2 = 0{\cdot}97$) and grass plots ($R^2 = 0{\cdot}60$), as well as for soil loss from bare plots ($R^2 = 0{\cdot}58$), but it could not predict soil loss under vegetation covers, either grass or shrubs. In all the treatments, the model underpredicted both runoff and soil loss and the standard errors of estimate were relatively high, being 4·67 mm ($P = 0{\cdot}95$). As EUROSEM was applicable to the arable and certain aspects of rangeland catchment, such as bare ground, it is likely that the approach of taking an effective parameter for vegetation properties across a plot may not be appropriate for spatially variable vegetation and that a different approach to erosion simulation may be required in this type of environment, or an acceptance that the response from rangeland plots may be too variable to predict with any confidence. Further testing of the model under a wider range of climatic and land use types is necessary to establish its applicability to semi-arid and rangeland conditions in general.

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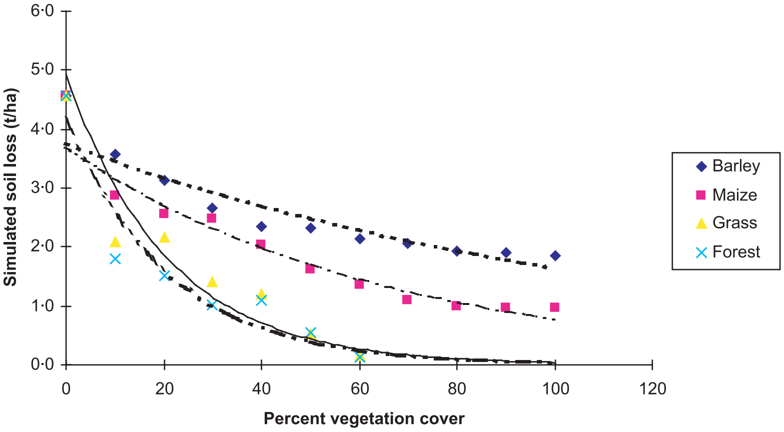

Figure 6. Simulation of soil loss with EUROSEM from four vegetation types. This figure is available in colour online at www.interscience.wiley.com/journal/espl.

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