Soil erosion simulations of land use scenarios for a small Loess Plateau catchment

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Abstract

Several land use scenarios were developed for the 3.5 km² Danangou catchment on the Chinese Loess Plateau. These scenarios consist of four groups of three scenarios each: one group is based on the present land use distribution, the other three (alternative land uses) on a redistribution of land use according to slope gradient, soil type, slope aspect and land form. For example, cropland areas are restricted to slope gradients smaller than 25%, 20% and 15%. All groups consist of one scenario that only uses present or alternative land use and two scenarios that apply simple forms of biological conservation practices (mulching, improved fallow) and mechanical conservation practices (contour ridges). The LISEM soil erosion model was used to simulate the effects of these different scenarios on erosion. To do this, a calibrated Lisem-data set for a real storm was used. The results show that the predicted erosion rates for woodland/shrubland are much lower than those for other land uses. According to the simulations, runoff and erosion decrease by about 10% if conservation measures are applied to the present land use, while the predicted decrease for the alternative land uses is much larger at between 40% and 60%. This large decrease can be explained by the fact that one of the main differences in the alternative land uses is that they have much more woodland/shrubland. Differences in predicted erosion rates between the different alternative land uses are caused by conversion of cropland to orchard/cash tree. The present study is one of the first attempts to use soil erosion modelling as a tool for optimising land use and management strategies to reduce runoff and erosion

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rates on the Chinese Loess Plateau. More research will be needed to validate obtained simulation results with actual field measurements.

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1. Introduction

Soil erosion on the Chinese Loess Plateau is a major problem because on-site it causes loss of arable land, while off-site it can cause silting up of rivers and reservoirs. In 1999, the Chinese government, aided by the Chinese Academy of Sciences (CAS), formulated new ambitious policies about the Loess Plateau. These policies aim to decrease erosion rates through changes in land use. In particular, these policies aim at a large decrease in cropland area so that all fields on slopes above a certain slope degree should be changed from cropland to other uses. The decrease in cropland should be accompanied by an intensification of the remaining cropland and by an increase in woodland, shrubland and orchards (cash trees). The idea is that in the long term the income of the farmers should increase once they get better yields from the remaining cropland as well as income from fruit trees and other cash trees. Since it takes time before the new land use can start to benefit the farmers, the government considers compensation to the farmers to make the change economically feasible for them.

The objective of the present study was to evaluate the effects of different land use scenarios on soil erosion in a small catchment on the Loess Plateau in China. The scenarios that were used in the present paper were developed based on a biophysical resource inventory, farmer's perception and the plans of the authorities on regreening the Loess Plateau. The scenarios not only specify land use, but also take into account several kinds of soil and water conservation measures.

To evaluate the effects of the different land use scenarios, the LISEM soil erosion model (De Roo et al., 1996; Jetten and De Roo, *in press*) was applied. LISEM is a physically based distributed erosion model that operates on storm basis. Although it has been shown repeatedly (e.g. Jetten et al., 1999) that such models cannot accurately predict future events they may be used to simulate different land use scenarios. In the case of scenarios, the same uncertainty in input data applies to all scenarios and one can therefore assume that the differences produced for the different simulations are in fact a consequence of the applied scenario changes.

2. Study area and methods

The study area was the Danangou catchment, Shaanxi Province, China. The catchment is a typical small Loess Plateau catchment with a catchment area of 3.5 km². Elevation in the catchment ranges from 1070 to 1370 m, and slope angles are steep. The climate is semi-arid, with average annual rainfall of slightly over 500 mm. More than 70% of the annual rainfall falls between June and September, mostly in a few heavy

storms. Erosion can be serious during such storms. Both arable land and gullies seem to be major sources of sediment during storms. One of the criteria used in selecting this catchment for research was the fact that up until now the amount of soil conservation measures in the catchment is limited. This allows us to compare simulation results with a no-conservation situation (the present situation). The farmers are, however, well aware of the erosion problem and are willing to use more conservation measures, but they have so far been unable to do so for financial reasons (Hoang Fagerström et al., [this issue](#)).

2.1. Land use

Soil physical properties that are needed for simulation could only be measured for a few land uses: cropland, orchard/cash tree, woodland/shrubland, wild grassland, vegetables and fallow. [Fig. 1](#) shows the present (1998) distribution of these land uses. The main land uses in the Danangou catchment are wild grassland and cropland. Wild grassland is mainly located on the steeper parts of the gully slopes as well as on the gully bottoms and was until recently used for grazing goats. This practice has ceased, since grazing was prohibited in September 1999. Cropland is located mainly on the hilltops and also on the relatively gentle slopes at lower elevation. The most common crops in the area are potato, millet, soybean, buckwheat and maize. Fallow land is mostly situated along the hilltops and woodland in the upper parts of some of the valleys.

2.2. Scenarios

The scenarios used in the present paper were developed based on:

- (1) A biophysical resource inventory in the area (1998–1999, e.g. [Messing et al., this issue \(a\),\(b\)](#)).
- (2) Farmer's perception as found in participatory approach studies (1998–1999, [Hoang Fagerström et al., this issue](#); [Messing and Hoang Fagerström, 2001](#))
- (3) The plans of the authorities on greening the Loess Plateau.

The scenarios are more fully described by [Chen et al. \(this issue\)](#). They can be divided into four groups of three scenarios each ([Table 1](#)). Each group uses a different land use map and the effects of biological measures (such as mulching and improved fallow) and mechanical measures (e.g. contour ridges) were evaluated separately. These measures are relatively simple and inexpensive, but labour-intensive. One group uses the 1998 land use map, the other groups use, respectively, 25°, 20° and 15° as the upper slope limit for cropland. The 15° limit scenario is considered a long-term scenario and the 25° and 20° limits are therefore short-term intermediate scenarios ([Chen et al., this issue](#)).

Compared to the present land use ([Fig. 1](#)), the scenario land use maps (15° map in [Fig. 2](#)) all have much more woodland/shrubland, while cropland area decreases according to the specified slope limits. The area of orchards also has increased significantly for the 20°

Fig. 1. Simplified land use map for 1998 (also in [Chen et al., 2003](#)).

Fig. 2. Scenario land use (15° cropland limit) for the Danangou catchment (also in [Chen et al., 2003](#)).

Table 1
Summary of land use scenarios

Scenario	Description
0	Present land use without conservation measures
0a	Present land use with biological conservation measures on cropland/fallow land
0b	Present land use with mechanical conservation measures on cropland/fallow land
1	Scenario land use with slope angle limit for cropland of 25°, ridges and grass strips on orchard/cash tree land
1a	Scenario land use with slope angle limit for cropland of 25°, with ridges and grass strips on orchard/cash tree land, biological measures on cropland/fallow land
1b	Scenario land use with slope angle limit for cropland of 25°, with ridges and grass strips on orchard/cash tree land, mechanical measures on cropland/fallow land
2	Scenario land use with slope angle limit for cropland of 20°, ridges and grass strips on orchard/cash tree land
2a	Scenario land use with slope angle limit for cropland of 20°, with ridges and grass strips on orchard/cash tree land, biological measures on cropland/fallow land
2b	Scenario land use with slope angle limit for cropland of 20°, with ridges and grass strips on orchard/cash tree land, mechanical measures on cropland/fallow land
3	Scenario land use with slope angle limit for cropland of 15°, ridges and grass strips on orchard/cash tree land
3a	Scenario land use with slope angle limit for cropland of 15°, with ridges and grass strips on orchard/cash tree land, biological measures on cropland/fallow land
3b	Scenario land use with slope angle limit for cropland of 15°, with ridges and grass strips on orchard/cash tree land, mechanical measures on cropland/fallow land

and 15° scenario groups. Fallow was considered part of the cropland area. Since the proposals suppose an intensification of agriculture on the remaining cropland (e.g. the use of fertilisers, improved fallow) it is likely that the proportion of cropland that is fallow will decrease in the future. In this paper, it was assumed that 1/5 of the cropland will be fallow. The actual distribution of fallow in Fig. 2 was generated by using randomly distributed fallow areas with minimum size of about 500 m². Table 2 lists the areas occupied by the different land uses. It shows that for the 25°, 20° and 15° land use maps there is a gradual decrease in cropland and fallow land (but maintaining the 4 to 1 ratio between them) and a gradual increase in orchard/cash tree. By definition, the change is limited to areas below 25°. The other land uses (including all slopes of more than 25°) remain unaffected for these scenario groups, so for these land uses and slopes, only the present land use scenario differs.

Table 2
Areas (%) occupied by the different land uses for the different land use maps

Land use	Present land use	25°	20°	15°
Cropland	35.4	21.0	13.0	6.7
Orchard/cash tree	2.4	0.0	9.5	17.8
Wood/shrubland	13.4	38.2	38.4	38.3
Waste/wild grassland	41.4	35.5	35.7	35.6
Vegetables	0.1	0.1	0.1	0.1
Fallow	7.3	5.2	3.2	1.6

Catchment area is 3.52 km².

2.3. LISEM implementation

The LISEM soil erosion model is a physically based distributed model. A distributed model has the advantage that it simulates erosion patterns within the catchment as well as sediment yield from the entire catchment. This should give information that can be useful to determine where soil and water conservation measures should be applied. Several recent studies (Takken et al., 1999; Hessel et al., 2003 (a)) have, however, shown that the spatial patterns of erosion as simulated with LISEM should be regarded with caution. LISEM simulates discharge and erosion for individual storms. It produces both an erosion map and a deposition map. Net erosion can be calculated by combining the two maps. For practical reasons we could in this paper only use the erosion map to present the results. For the period 1998–1999 data on only three storms could be collected. Calibration on these storms showed that a separate calibration for each storm is preferable (Hessel et al., this issue (a)). This makes the use of a so-called design storm less appropriate: such a storm can never be calibrated since it is a hypothetical storm. Therefore, one of the three storms measured had to be used. One of these storms was so small that it did not produce much erosion, while another was too much concentrated in a part of the catchment to make it useful for catchment-wide evaluation of scenarios. The only possibility was therefore to use the data of the storm that occurred on August 1, 1998. For the simulations, the calibrated input data set for the 980801 storm was used (Table 3). All simulations were carried out with LISEM version 1.63.

The total catchment area of 3.5 km² makes simulation with a grid size smaller than 10 m impractical. On the other hand, many soil conservation measures are much smaller than 10 by 10 m and can therefore not be implemented directly, e.g. by changing the Digital Elevation Model (DEM). Instead, such measures must be incorporated by changing other parameters that will be influenced by the original measure. For example, it can be expected that the use of contour ridges will increase infiltration. Since the ridges cannot be incorporated directly, one can then increase for example saturated conductivity to produce such an increase in infiltration. In this way, all the proposed measures were translated into changes of input parameters for the LISEM model (Table 4). Table 4 gives assumed

Table 3
LISEM input data set for the event of August 1, 1998

	C	O/C	W/S	WG	V	F
Plant height (m)	0.68	3.66	6.50	0.38	0.68	0.32
Plant cover	0.38	0.28	0.88	0.52	0.38	0.10
Leaf area index	1.64	3.20	7.37	0.60	1.64	0.78
Cohesion (kg cm ⁻²)	0.09	0.11	0.10	0.12	0.09	0.10
Added cohesion (kPa)	2	2	2	2	2	2
Random roughness (cm)	1.16	1.11	0.75	0.90	1.16	1.21
Aggregate stability (median drop no.)	11.1	7.8	28.8	17.3	11.1	8
Manning's <i>n</i>	SD	0.092	0.184	0.091	SD	0.079
Ksat (cm day ⁻¹)	7.59	33.63	26.24	18.92	7.59	7.59

C = cropland, O/C = orchard/cash tree, W/S = woodland/shrubland, WG = wild grassland, V = vegetables, F = fallow.

SD = slope dependent, Manning's *n* is calculated from slope, see Hessel et al. (this issue (b)).

Table 4
Effects of conservation measures on LiseM input parameters

	Cropland biological	Fallow biological	Cropland mechanical	Orchard ridges with grass strips
Plant height	1	0.5 ^a	1	1
Plant cover	1.05	1.25	1	2
Leaf area index	1.05	1.25	1	2
Cohesion	1	1	1	1
Added cohesion	1	1.25	1	1.25
Random roughness	2	1	1.5	1.5
Aggregate stability	2	1	1	1.25
Manning's <i>n</i>	0.15 ^a	1.1	1.25	1.25
Saturated conductivity	1.25	1.25	1.1	1.25

^a These values are not multiplication factors but real values.

multiplication factors for the original LISEM input data set (Table 3): for example a value of 1.25 for 'fallow biological' plant cover means that the data that apply to the 980801 storm were multiplied by 1.25. Hence, 'fallow biological' plant cover was the product of 0.10 (Table 3) and 1.25 (Table 4), and equalled 0.125.

3. Results

Fig. 3 shows a classified version of the present land use erosion map produced by LISEM. Classification was done using the classification scheme shown in Table 5. This was

Fig. 3. Classified LISEM erosion map for the present land use and the August 1, 1998 storm.

Table 5
Classification scheme for LISEM erosion maps

Erosion class	Lower boundary	Upper boundary
Negligible	0	2.5
Slight	2.5	10
Moderate	10	25
Serious	25	100
Severe	100	2000

Erosion is given in tonne ha⁻¹.

done to give a better map readability. Without the classification the map appearance would be totally dominated by a few very high values. It is important to realize that the values for lower and upper boundaries in Table 5 apply to the 980801 storm only. For individual storms in the Danangou catchment, the lower boundary of severe soil erosion will therefore not always be 100 tonne ha⁻¹. The 980801 storm was not a big storm (its recurrence interval was probably below 1 year), so much larger storms can occur. It is well possible that for such storms an erosion amount of 100 tonne ha⁻¹ should be considered moderate only.

For a large area in the southern part of the catchment, no serious erosion was predicted (Fig. 3). This is caused by the fact that, according to the measured rainfall data, less rain fell in this area during the 980801 event. The amount of erosion therefore also was less. Comparison of Figs. 1 and 3 indicates that other areas with negligible erosion rates for the 980801 storm were mainly woodland areas. A zone along both sides of the main gullies also had little erosion since this area is underlain by bedrock, which has a much higher cohesion, both in reality and in the model. The hilltop areas generally had slight or moderate erosion rates (Fig. 3), while the steeper parts of the slopes had serious or severe erosion rates. Apart from woodland not much difference in erosion is visible for the different land uses.

Fig. 4 shows the results of a scenario run with the present land use, but with biological conservation measures (scenario 0a) on cropland/fallow. In Fig. 4, the results of scenario 0a are compared to the results of scenario 0. The scenario 0a result was first divided by the scenario 0 result and then classified. Hence, Fig. 4 shows relative change, so that the actual amounts of erosion involved need not be large. Comparison of Figs. 1 and 4 shows that erosion rates decreased for the cropland and fallow areas and that they remained much the same for the other land uses. In some areas, an unexpected increase in erosion was simulated. Since Lisem is a complicated model it is difficult to trace the cause of this increase. One possible explanation would be that there is some sort of feedback operating: for example if the amount of erosion in an upstream pixel was decreased but the amount of water was not, more erosion could occur in the pixel than before.

Fig. 5 shows the results of the scenario land use with 15° cropland limit. The classification scheme in Table 5 is used, so the map can be compared directly to Fig. 3. It is evident that the erosion in the catchment has decreased. The area with negligible erosion rates has more than doubled in size, while the other erosion classes have all decreased in area. Comparison with Fig. 2 shows that like in Fig. 3 the negligible erosion rates mainly occurred under woodland/shrubland. The large decrease in predicted erosion

Fig. 4. Results for the present land use with biological conservation measures (scenario 0a) on cropland/fallow.

Fig. 5. Predicted erosion for the scenario land use with 15° cropland slope limit (scenario 3).

is therefore probably a direct consequence of the increase in woodland/shrubland area. Table 6 shows that erosion in woodland decreased from present land use to the 25° scenario, even though woodland area increased significantly (Table 2). Comparison of Tables 2 and 6 shows that erosion for cropland and fallow land steadily decreased with decreasing area occupied by these land uses. Table 6 also shows a decrease in erosion for wasteland/wild grassland from the present land use to the 25° scenario. However, from the present land use to the 15° scenario erosion in the catchment became increasingly dominated by erosion in wasteland/wild grassland. Table 7 shows that total soil loss (erosion minus deposition) from the catchment was much larger for scenario 0 than for the other scenarios. The differences in predicted soil loss between scenarios 1, 2 and 3 were, however, relatively small. Since Table 2 shows that woodland/shrubland areas in scenarios 1, 2 and 3 were equal, but much smaller in scenario 0 it is very likely that the woodland/shrubland area was indeed the cause of this difference in soil loss between scenario 0 and the other scenarios. Another possible cause would be that cropland was restricted to less steep slopes in scenarios 1 to 3, but Table 6 shows that erosion rates for wild grassland were also high. Hence, if the cropland had been replaced by wild grassland there might not have been a decrease in erosion at all. Fig. 5 also shows that in some areas erosion rates have increased in comparison to scenario 0. Comparison of Figs. 1 and 2 shows that this mainly applied to areas that were woodland/shrubland in scenario 0 and had in scenario 3 become something else, e.g. wild grassland.

Apart from the erosion/deposition maps, LISEM also generates time series of discharge and erosion for the outlet of the catchment. These data can be used to create hydrographs and sedigraphs for the catchment outlet. The upper three curves in Fig. 6 show that using conservation measures in the present land use (scenario 0) decreased the peak discharge 10% to 15%, while the reduction was much larger when applying scenarios 1, 2 and 3 (50–60%). The peak discharge for the alternative scenarios arrived marginally earlier with a lower cropland slope limit (Table 7a). This indicates that with the decrease in permissible slope angle the remaining discharge is generated closer to the stream: since water velocity depends on water height a smaller amount of water would have a lower velocity and a retarded peak. The sedigraphs (not presented here) showed much the same trend as the hydrographs.

Relatively small decreases are shown in peak discharge, total discharge and total soil loss for the conservation measures for all scenarios (ranging from 2% to 15%), whereas large decreases (ranging from 36% to 60%) are shown for the alternative land use

Table 6
Erosion (tonnes) for different land use scenarios

Land use	Present land use	25°	20°	15°
Cropland	4046	1984	1109	487
Orchard/cash tree	161	0	406	663
Wood/shrubland	289	261	221	177
Waste/wild grassland	9381	6940	6735	6550
Vegetables	45	45	44	43
Fallow	1206	602	416	137
Total	15,128	9831	8932	8057

Table 7
Summary of simulation results for the catchment outlet

(a) Absolute values of runoff and erosion

Scenario	Time to peak (min)	Qpeak (l s ⁻¹)	Qtotal (m ³)	Total soil loss (tonnes)
0	40.25	10,703	10,727	2830
0a	40.5	9193	9555	2423
0b	40.5	9806	10,121	2613
1	40.75	5566	6836	1482
1a	39.75	5083	6083	1309
1b	40.0	5248	6497	1403
2	39.75	4884	6047	1284
2a	39.75	4613	5460	1161
2b	39.75	4743	5800	1231
3	39.5	4541	5351	1125
3a	39.5	4358	4946	1040
3b	39.5	4459	5188	1090

(b) Percentage decreases in runoff and erosion compared to scenario 0

Scenario	Qpeak	Qtotal	Total soil loss
0	0	0	0
0a	14.1	10.9	14.4
0b	8.4	5.6	7.7
1	48.0	36.3	47.6
1a	52.5	43.3	53.7
1b	51.0	39.4	50.4
2	54.4	43.6	54.6
2a	56.9	49.1	59.0
2b	55.7	45.9	56.5
3	57.6	50.1	60.2
3a	59.3	53.9	63.3
3b	58.3	51.6	61.5

(c) Percentage decreases in runoff and erosion compared to the scenarios with no conservation measures

Scenario	Qpeak	Qtotal	Total soil loss
0	0	0	0
0a	14.1	10.9	14.4
0b	8.4	5.6	7.7
1	0	0	0
1a	8.7	11.0	11.7
1b	5.7	5.0	5.3
2	0	0	0
2a	5.5	9.7	9.6
2b	2.9	4.1	4.1
3	0	0	0
3a	4.0	7.6	7.6
3b	1.8	3.0	3.1

scenarios compared with scenario 0 (Table 7b,c). The decrease in total discharge was smaller than the decrease in peak discharge and total soil loss. From Table 7b,c, it can be deduced that this was probably caused by an unexpectedly small total discharge for scenario 0. If Qtotal for scenario 0 would be somewhat higher all the reductions of Qtotal

Fig. 6. Predicted hydrographs for different land use scenarios.

(Table 7b) would become larger and the results for scenario group 0 would then also be more in line with the results of the other scenario groups in Table 7c. For scenario groups 1 to 3 the decrease in peak discharge was always smallest, with total discharge and total soil loss being very similar (Table 7c). Thus, scenarios 1, 2 and 3 were similar, with predicted runoff and erosion differences between them of only 20–25% and scenario group 0 was clearly different (Table 7). The 20% difference between scenarios 1 and 3 was caused by conversion of cropland to orchard/cash tree. For all scenarios, the decrease in predicted runoff and erosion rates as a result of conservation measures was relatively small (2–12%). The effect of these measures decreased from scenarios 0 to 3 (Table 7c). This was to be expected since the surface area on which these measures were applied decreased from scenarios 0 to 3, while erosion from other parts of the catchment was unaffected by these conservation measures. The biological measures were always a little more effective than the mechanical measures (Table 7c).

4. Discussion

The present study is one of the first attempts to use soil erosion modelling as a tool for optimising land use and management strategies to reduce runoff and erosion rates on the Chinese Loess Plateau. This study shows that the results obtained with the LISEM model are consistent with each other, i.e. that the difference simulated for the different scenarios can be explained from differences in input data and land use maps. To perform the simulations several assumptions were made.

The first is that LISEM can be used for scenario simulations. To evaluate this assumption, further research into the distribution of erosion as simulated by LISEM is needed because several recent studies (Takken et al., 1999; Hessel et al., 2003 (a)) have

shown that LISEM might not predict erosion patterns correctly. This might have implications for its use in scenario simulations as well. Another potential problem with LISEM is that total soil loss is often a fairly small difference between large erosion and large deposition values. The erosion amounts shown in Table 6 are for example much higher than the total soil loss given in Table 7. This means that simulated soil loss from the catchment will be much influenced by simulated deposition, so that conclusions based on simulated erosion might not be applicable to soil loss.

The second assumption is our use of multiplication factors. It is important to realize that the effect that is predicted for SWC measures (when compared to land use change) is determined by the values of the multiplication factors that were assumed (Table 4). At present it is difficult to judge to what degree the values of the multiplication factors used are valid. More data on the effect of SWC measures should be gathered to be able to select values with a higher degree of certainty. Related to this assumption is the assumption that the measured data (Table 3) are correct.

A third assumption is that the selected storm is representative. In reality, it seems likely that the effect of soil and water conservation measures will depend on the intensity and size of a storm. Farmers in the area also indicate that for really large storms it does not matter what conservation measures you have, because there will be severe erosion anyway.

Thus, more research is needed before we can say to what degree the simulation results of LISEM reflect reality. LISEM is a state of the art erosion model, and other erosion models will suffer from similar limitations. Therefore, care must be taken not to read too much into scenario simulation results. Scenario simulations with erosion models give us useful insights into what might happen, but they do not tell us what will happen.

5. Conclusions

The LISEM scenario simulations predict that a decrease in runoff volume and erosion amount of about 5–15% can be reached by implementing conservation methods with the present land use distribution (scenarios 0a and 0b). Changing the land use according to the slope-angle-based proposals defined in the scenarios 1, 2 and 3 is predicted to have a much larger effect; discharge decreases by about 40–50%, while erosion decreases by 50–60%. The differences between different maximum permissible slopes for cropland were predicted to be only about 20–25%. The LISEM simulations do not show a clear difference in erosion rates between most land uses; only woodland/shrubland and orchard/cash tree seem to have clearly lower erosion rates than the other land uses. The large increase in woodland/shrubland area in the scenario 1, 2 and 3 land use maps is therefore a direct cause for the large decrease in predicted erosion, while the decrease from scenarios 1 to 3 was caused by conversion of cropland to orchard/cash tree. More research is needed before we can say to what degree the simulation results of LISEM reflect reality.

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