Topographic differentiation simulation of crop yield and soil and water loss on the Loess Plateau

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Abstract: De-farming slope farmland has been an effective measure in recent years for the improvement of the eco-environment and the mitigation of soil and water loss on the Loess Plateau. This paper, taking the Yangou Basin as a case study and using day-by-day meteorological data of Yan’an station in 2005, simulated and analyzed the quantitative relation between crop yield, soil and water loss and topographic condition with the aid of WIN-YIELD software. Results show that: 1) topographic gradient has important influence on crop yield. The bigger gradient is, the lower the crop yield. Yields of sorghum and corn decrease by 15.44% and 14.32% respectively at 25° in comparison to the case of 0°. In addition, yields of soya, bean and potato decrease slightly by 5.26%, 4.67% and 3.84%, respectively. The influences of topographic height and slope aspect on crop yield are slight. 2) Under the same topographic condition, different crops’ runoff and soil loss show obvious disparity. Topographic gradient has important influence on soil and water loss. In general, the changing trend is that the soil and water loss aggregates with the increase of gradient, and the maximal amount occurs around 20°. The influence of topographic height is slight. Topographic aspect has a certain effect, and the fundamental characteristic is that values are higher at the aspect of south than north. 3) Topographic gradients of 5° and 15° are two important thresholds. The characteristic about soil and water loss with the variation of topographic gradients show that: the slope farmland with gradient less than 5° could remain unchanged, and the slope farmland more than 15° should be de-farmed as early as possible.

Keywords: crop yield; soil and water loss; topographic differentiation; Loess Plateau

1 Introduction

Soil erosion and eco-environmental deterioration due to Loess Plateau’s inherent vulnerability of natural ecosystems and long-term improper human activities have commonly been subject to the relevant government departments and academic institutions (Xu, 2000; Jing, 1999; Zhou and Yang, 2002; Lu et al., 2004). Since the late 1950s, studies have been done from the perspectives of various aspects. Many scholars have drawn a conclusion that
de-farming slope farmland is the key point of erosion control and eco-environmental restoration on the Loess Plateau (Tang et al., 1998; Hu and Jin 1999; Cai et al., 1996; Chen and Fu 2001; Fu et al., 2001; Xu 1997). At the same time, the practical patterns such as “re-building terrace and de-farming” (RTD), “dam system and permanent control” (DSPC) and “relieving and de-farming” (RD) have emerged successively and achieved good results (Tian, 2003; Kang, 1993). RTD is a kind of integrative ecological de-farming pattern, de-farming slope farmland through building terraces and guaranteeing the basic farmland and self-sufficiency in food (Xu et al., 2002). DSPC is based on the viewpoint that building silt storage dams and developing high-yield agriculture will help to de-farm slope farmland and completely control soil erosion (Kang, 1993). RD is the shortened form of the ecological de-farming policy named “de-farming and recovering forest (grass), having a bare mountain green, awarding a contract to individual and substituting grain for relieving”. In order to effectively weaken the menaces of stopped flowing and flood disaster in the middle or lower reaches of some large rivers (Qian et al., 2001; Liu and Cheng, 2000), RD has been carried out on the Loess Plateau and the upper reaches of the Yangtze River since 2000 (Tian et al., 2000; Peng et al., 2002). From the above mentioned, we easily find that these resultful de-farming patterns took measures to be able to help improve farmers’ livelihood for the purpose of de-farming slope farmland. To promote de-farming slope farmland on the Loess Plateau, this paper takes the Yangou Basin as a case, simulates crop yield, soil and water loss of slope farmland under different terrain height, gradient and aspect with the aid of WIN-YIELD software first, and then analyzes the quantitative relation between crop yield, soil and water loss and topographic condition.

2  Study site, software and data

2.1  Study site

The Yangou Basin is situated at 36°28′00″–36°32′00″N and 109°20′00″–109°35′00″E. The gully mouth is 3 km away from Yan’an city. It belongs to the secondary tributary of the Yanhe River, with a flow direction from southeast to northwest. Its length is 8.6 km and its area is 48 km². The altitude of the basin is between 986–1425 m, where the southeast is higher than the northwest. The gradient of the main gully is 2.41‰, and the gully density is 4.8 km/km², therefore this basin is a typical loess hilly-gully area. The terrain gradient of the basin is mostly composed of steep hill slopes (Xu et al., 2002). Land in the basin with gradients over 25° occupies 51.91%, between 15° to 25°, 28.75%, and less than 15°, 19.34%. The climate changes from semi-humid to semi-arid. The annual average temperature is 9.8 °C and the annual precipitation is about 558.4 mm. The natural vegetation consists of secondary natural forests, which have been seriously degraded. Artificial vegetation is mainly composed of locusts, poplars and other shrubs. More than 90% of the soil is loessal soil, furthermore, it is semi-mature soils with low fertility. According to the field surveyed data (Ju et al., 2000), the discharge of the Yangou river in 1998 was 0.0025 m³/s. The total annual runoff was 378,300 m³, of which flood runoff accounted for 79.3%. The total volume of silt in the gully mouth was 133,950 t, and soil erosion modulus was 2856 t/km²·a. The flow of perennial drainage, total volume of silt and soil erosion modulus in 2007 were 51,340 m³,
1556.587 t and 33.12 t/km$^2$ a, respectively.

Since 1996, with the implementation of the World Bank Financed Project and NKTRDP (National Key Technologies R & D Programme), land use structure of the Yangou Basin has undergone considerable change (Xu and Sidle, 2001). In 1997, there were 1831.1 ha of farmland in the basin, making up 39.06% of the total area. Slope farmland was 1617.6 ha, accounting for 88.34% of the farmland, and 66.32 ha of terraces accounted for 1.41%. In 2003, farmland decreased to 593.35 ha, down to 12.63% of the total area. Terraces increased to 446.17 ha, up 9.5%, and the slope farmland was totally de-farmed. There are 14 administrative villages and Goukou district in Yangou Basin. By the end of 2006, the total population of the 14 villages was 3133, with a density of 67.8 person/km$^2$. The rural economy mainly relies on the agriculture, supported by farming, forestry and stock raising. The per capita income of rural residents was 2168 yuan in 2006 and derived mainly from crop-plantation and apple-plantation. The crops are mainly corn, potato, sorghum, soybean, mung bean, black soy bean, and a small amount of artificial alfalfa.

### 2.2 WIN-YIELD software

WIN-YIELD is a software tool providing the necessary technology for adaptive and sustainable land management which could assist in answering this question: “What yields can we expect on a particular plot, with a specific crop, assuming some sort of climate and applying predefined management?” The four major components of the question (plot, climate, management, yield of crop) require preparation of the data. This software has been a collaborative effort of the University of Toronto (Toronto, Canada), the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences (Beijing, China) and the local and regional governments of Shaanxi Province and Inner Mongolian Autonomous Region of China, funded by the Canadian International Development Agency (CIDA) and the Association of Universities and Colleges of Canada (AUCC). With the ten-old years of this project completed in 2000, the general objectives were focused on land management decision-making--its complex socio-economic and biophysical circumstances. The WIN-YIELD is composed of models of crop yield and water-soil loss. The crop yield model, based on the Wageningen model and the demonstration research results on the Loess Plateau, includes series of empirical, mechanism and semi-mechanism models (Liu et al., 2002; Xie and Kiniry, 2002; Xu, 1999). The water-soil model based on the experiment includes series of regression models. Parameters and data (Table 1) are listed in one initialization file (Liu et al., 2002). The input and output files are all in text (.txt) format, and output files include Yield Data File, Sediment Data File and Hydrologic Data File.

### 2.3 Data sources and preferences

Data are involved with socioeconomic data, meteorological data, crop types data, land unit data, and parameters of soil properties, geomorphological types and land use types. Socioeconomic data come from farmer sampling survey data and township statistical data. Meteorological data include nine indexes as daily mean temperature, precipitation, rainfall duration, cloudiness, evaporation, mean relative humidity, minimum relative humidity, daytime wind velocity and night wind velocity of Yan’an station in 2005. The crops simulated include corn, potato, sorghum, soya and bean. Designing of Land Unit Input File follows the
Table 1  Parameters, data files and data items inputted in WIN-YIELD initial interface

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Meteorology input file</th>
<th>Precipitation input file</th>
<th>Land unit input file</th>
<th>Crop distribution input file</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station name.</td>
<td>Calendar year*</td>
<td>Calendar day.</td>
<td>Coding of land unit.</td>
<td>Coding of land unit.</td>
</tr>
<tr>
<td>Latitude/Longitude.</td>
<td>Mean temperature</td>
<td>Amount of precipitation</td>
<td>Area (m²).</td>
<td>Number of entries of</td>
</tr>
<tr>
<td>Soil parameter K.</td>
<td>(°Celsius)</td>
<td>(mm).</td>
<td>Elevation (m).</td>
<td>crop data on this row.</td>
</tr>
<tr>
<td>Soil parameter R.</td>
<td>Mean relative humidity</td>
<td>Duration of precipitation</td>
<td>Gradient (°).</td>
<td></td>
</tr>
<tr>
<td>Sensitivity analysis</td>
<td>Minimum relative</td>
<td>often 0 if not</td>
<td>Aspect (°).</td>
<td></td>
</tr>
<tr>
<td>crop parameter.</td>
<td>humidity (%)</td>
<td>known (minute).</td>
<td>Soil type.†</td>
<td></td>
</tr>
<tr>
<td>Ground-water storage</td>
<td>Cloud cover (%)</td>
<td></td>
<td>Landform type.‡</td>
<td></td>
</tr>
<tr>
<td>depth.</td>
<td></td>
<td></td>
<td>Land use type.§</td>
<td></td>
</tr>
<tr>
<td>Root growth rate.</td>
<td>Day wind velocity (m/s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Period of growth.</td>
<td>Night wind velocity (m/s)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: * Calendar year: 1-365/366
† Soil type: 11: sandy, yellow; 12: clay, yellow; 13: loam, yellow
‡ Landform type: 1: terrace; 2: slope land; 3: gully slope land; 4: gully bottom
§ Land use type: 1: farmland; 2: woodland; 3: unused land

tendency of elevation, gradient and aspect:

a) Designing Land Unit Files based on the tendency of elevation. Eight land units are divided between 1050 and 1400 m at an interval of 50 m. Parameters of the land unit were an area of 1 ha, a gradient of zero, an aspect of 180° (south), soil type as 11 (sandy, yellow), landform type as 1 (terrace) and land use type as 1 (farmland).

b) Designing Land Unit Files based on the tendency of gradient. Thirteen land units are divided between 0° to 30° at an interval of 2.5°. Parameters of the land unit were an area of 1 ha, an elevation of 1100 m, an aspect of 180° (south), soil type as 11 (sandy, yellow), landform type as 2 (slope land) and land use type as 1 (farmland).

c) Design Land Unit Files based on the tendency of aspect. Sixteen land units are divided between 0° to 360° at an interval of 22.5°. Parameters of the land unit were an area of 1 ha, an elevation of 1100 m, a gradient of 15°, soil type as 11 (sandy, yellow), landform type as 2 (slope land) and land use type as 1 (farmland).

3 Results and discussion

3.1 Topographic differentiation simulation of crop yield

3.1.1 Changes of crop yields with topographic height

Planting different crops in the Yangou Basin, changes of the simulation data of yield with topographic height show these fundamental characteristics: In the case of the same elevation, the simulation data of different crops’ yields vary tremendously. Bean’s yield is the lowest, and the simulation data are 1037 to 1043 kg/hm²; potato’s yield is the highest, and the simulation data are 11,138 to 11,190 kg/hm², 10.7 times that of bean; other crops’ data are corn of 2503 to 2558 kg/hm², sorghum of 2498 to 2561 kg/hm², and soya of 2016 to 2035 kg/hm². However, the tendency of the simulation data of yield for different crops shows difference with the increase of elevation. The simulation yields of corn, sorghum, soya and bean drop slightly with the increase of elevation, while potato’s yield increases slowly. As a whole, elevation has little influence on crop yield.
3.1.2 Changes of crop yields with topographic gradient

The tendency of the simulation data of yield for different crops with the topographic gradient change on a height of 1100 m and aspect of south slope farmland of the Yangou Basin in 2005 is shown in Figure 1. Planting different crops in the Yangou Basin, changes of the simulation data of yield with topographic gradient show basic characteristics as follows:

a) With the increase of topographic gradient, the simulation data of five crops’ yields show a decreasing trend. The yields of potato, corn, sorghum, soya and bean are 11,299 kg/ha, 2612 kg/ha, 2507 kg/ha, 2073 kg/ha and 1050 kg/ha on topographic gradient of 0°, respectively, while the yields decrease to 10,865 kg/ha, 2238 kg/ha, 2120 kg/ha, 1964 kg/ha and 1001 kg/ha on gradient of 25°, respectively.

b) With the increase of topographic gradient, the simulation data of five crops’ yields show a diverse decreasing trend. Yields of sorghum and corn decrease sharply with the gradients between 0° and 25°. They decline by 15.44% and 14.32% respectively at 25°, being the largest decreasing magnitude in comparison to the case of 0°. Yields of soya, bean and potato decline slightly, falling by 5.26%, 4.67% and 3.84%, respectively.

c) As a whole, topographic gradient strongly influences crop yield. The yield declines as the gradient rises. Different crops have different sensitivity to the variation of gradients. If we define percentage of crop yield change due to per degree of slope increase as sensitivity of yield versus gradient change, then the sensitivities of five crops would be sorghum 0.62%, corn 0.57%, soya 0.21%, bean 0.19% and potato 0.15% orderly.

Figure 1  Changes of crop yields with topographic slope in the Yangou Basin in 2005

3.1.3 Changes of crop yields with topographic aspect

The tendencies of the yield change for farming different crops with topographic aspect on the height of 1100 m and gradient of 15° slope farmland of the Yangou Basin in 2005 are shown in Figure 2. Planting different crops in the Yangou Basin, changes of the simulation data of yield with the topographic aspect show these fundamental characteristics: From north to south by clockwise rotation the simulation data decrease gradually as the aspect increases, the data are the least when aspect was due south (as 180°). Then from south to north, the data increase. As the aspect is due north (0° or 360°), the data of potato, corn, sorghum, soya and bean are 11,225 kg/ha, 2563 kg/ha, 2477 kg/ha, 2059 kg/ha and 1042 kg/ha, respect-
Figure 2  Changes of crop yields with topographic slope aspect in the Yangou Basin in 2005

tively. As the aspect is due south (180°), the data are 11,191 kg/ha, 2456 kg/ha, 2337 kg/ha, 2013 kg/ha and 1030 kg/ha, falling by 0.30%, 4.17%, 5.65%, 2.23% and 1.15%, respectively. This shows that yields of crops have been affected to some extent by the topographic aspect, but generally the aspect has slight effect on crops yields except corn and sorghum.

3.2  Topographic differentiation simulation of soil and water loss

3.2.1  Changes of soil and water loss with topographic height

Plantsing different crops in the Yangou Basin, changes of the simulation data of runoff and sediment load with topographic elevation show: Data of runoff and sediment load of the same crop are unaffected by the elevation change, but there is a notable difference between different crops. The simulation data of runoff and sediment load on the terraced field for planting crops at 1100 m above sea level of the Yangou Basin in 2005 are shown in Table 2. As shown in Table 2, data of runoff are the biggest for planting sorghum, reaching 46.42 mm, followed by corn and potato of 38 mm, runoffs of soya and bean are the least, approximately 35 mm. A close relationship was found between sediment load and runoff. Sorghum’s sediment load is the highest, being 4002 t/km²⋅a, and the other crops’ sediment loads are below 3340 t/km²⋅a. Compared with sorghum, benefit of soil and water conservation is soya of 25.9%, bean of 24.4%, potato of 19.9% and corn of 16.6%, indicating that the Yangou Basin is unsuitable for sorghum.

3.2.2  Changes of soil and water loss with topographic gradient

Changes of runoff and sediment load for planting corn, potato, soya and bean on slope farmland at an elevation of 1100 m and aspect of due south in the Yangou Basin of 2005 are shown in Figure 3. The changing tendency of runoff among these four crops are almost the same in the Yangou Basin as shown in Figure 3a. Runoff changes slowly from 0° to 17.5°; then runoff rises rapidly from 17.5° to 20° and peaks at 20°; it falls sharply from 20° to 22.5° and then shows a trend of gentle increase. Runoff of 17.5° slope farmland as planting corn increases by 0.813 mm or 2.10% compared with that of 0°. It rises by 10.99 mm or 27.78% from 17.5° to 20°, while it declines by 10.52 mm or 20.81% from 20° to 22.5°, and rises by 0.98 mm or 2.44% from 22.5° to 30°. Throughout analysis of the relationship of runoff change and topographic gradient, the unusual section of gradients were found between 17.5° to 22.5°, which should be given more attention.
Table 2 The simulation data of runoff and sediment load on the terraced field for farming crops at 1100 m above sea level in the Yangou Basin in 2005

<table>
<thead>
<tr>
<th>Crop</th>
<th>Runoff (mm)</th>
<th>Sediment load (t km⁻²·a⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potato</td>
<td>37.176</td>
<td>3205</td>
</tr>
<tr>
<td>Corn</td>
<td>38.731</td>
<td>3339</td>
</tr>
<tr>
<td>Sorghum</td>
<td>46.420</td>
<td>4002</td>
</tr>
<tr>
<td>Soya</td>
<td>34.407</td>
<td>2966</td>
</tr>
<tr>
<td>Bean</td>
<td>35.116</td>
<td>3027</td>
</tr>
</tbody>
</table>

Figure 3 The change of runoff and sediment load with terrain gradient on the slope farmland for crops of the Yangou Basin in 2005

The tendencies of sediment load changes with the increase of gradient are also the same among four crops in the Yangou Basin as shown in Figure 3b. Sediment load increases slowly from 0° to 5°, up by 10 t/km²·a or 0.30%; it rises by 751 t/km²·a or 22.43% at a moderate speed from 5° to 15°; and it rises sharply by 1989 t/km²·a or 48.52% from 15° to 20°. Sediment load declines rapidly by 453 t/km²·a or 7.44% from 20° to 22.5°, while it rises smoothly by 305 t/km²·a or 5.41% from 22.5° to 30°.

Analysis of soil and water loss with the variation of topographic gradient shows that: gradients of 5° and 15° are the available thresholds of topographic gradient on slope farmland. Gradient of 5° is the threshold for transforming slope into terraces, which means that slope farmland below 5° could not be transformed into terraces. Gradient of 15° is the threshold of returning cultivated land to forests or pastures, so the slope farmland more than 15° should be de-farmed as early as possible. Based on the simulation results of Tang Keli’s experiment (Tang et al., 1998), it should take 17°–18° as the de-farming threshold. Furthermore, abnormal data of soil and water loss with a gradient of around 20° are resolved by hydrodynamics mechanism for soil erosion. Based on the study results of Hu Shixiong (Hu and Jin 1999), serious soil erosion always occurs between gradients of 20° and 22° on slope farmland of the Loess Plateau.

3.2.3 Changes of soil and water loss with topographic aspect

The tendencies of runoff and sediment load changes with the topographic aspect for planting corn, potato, soya and bean on slope farmland with an elevation of 1100 m and gradient of 15° in the Yangou Basin are shown in Figure 4. This shows that: (1) The tendencies of runoff
and sediment load changes following the aspect are all the same for corn, soya and bean. Runoff and sediment load increases slowly from 0° to 180°, and reaches to the maximum on aspect of 180°; and it declines steadily from 180° to 360°. (2) The tendency of runoff and sediment load changes following the topographic aspect for planting potato is different from the other three crops between aspects of 112.5° and 247.5°, and shows a bow subsidence. (3) Topographic aspect has a certain effect on runoff and sediment load in fields of these four crops, but not a very great influence. The differences of runoff and sediment load between the highest and lowest with change of aspect for planting corn are 0.46 mm and 48 t/km²·a, and potato of 0.39 mm and 41 t/km²·a, soya of 0.28 mm and 29 t/km²·a, and bean of 0.33 mm and 34 t/km²·a.

4 Summary and conclusions

Topographic gradient has an important influence on crop yield, the bigger gradient and the lower crop yield, and the influences of topographic height and slope aspect on crop yield are slight. The suitable crops in the Yangou Basin are potato, corn, soya and bean. Sorghum is not suitable for planting on large scale because of the poor soil and water conservation benefits.

Under the same topographic condition, different crops’ runoff and soil loss show clear differences. The benefit of soil and water conservation from high to low ranks soya, bean, potato, corn and sorghum.

Topographic gradient also has an important influence on soil and water loss. The basic changing tendency is the bigger gradient and the more soil and water loss, but the influences of topographic height and slope aspect are slight.

Topographic gradients of 5° and 15° are two important thresholds. Topographic gradient of 5° is the lowest index point of changing slope farmland to terraces, and the slope farmland less than 5° could be retained. The slope farmland more than 15° should be de-farmed as early as possible.

References

Cai Qiangguo, Luk Shiuhung, Wang Guiping et al., 1996. Process-based soil erosion and sediment yield model in...


