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ORIGINAL ARTICLE

Influence of land terracing on agricultural and ecological environment in the loess plateau regions of China

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Abstract The combination of ecological fragility and agricultural activity in the loess hilly–gully regions of western China has received broad environmental concerns. In this region, rainfall and soil moisture can fatally influence crop production under dry land farming. In this study, field experiments were conducted, from March 2001 to September 2005, to demonstrate the variation of soil moisture and fertilizer contents at different depths in slope and terraced lands, and to evaluate the ecological impacts and economic benefits in the terraced land of Loess Plateau. The results of both field test and Grey model (GM) calculation show that the terraced land, as compared to the sloping land, in the agricultural area of the Loess Plateau tends to store and retain much water, promoting more favorable interactions between water and fertilizer. During the months from March to June of the year with less rainfall, the water supply for crop growth is mainly derived from the deep storage of soil moisture accumulated from July to September of the previous year. The field experiments indicate that the crop yield of the 3-year-old terraced lands was 27% higher than that of the sloping lands with slopes greater than 10°, and that the crop yield can increase by 27.07 to 52.78% in the following cultivation years. In particular, potato was found to be more drought-resistant than winter wheat, thus it is more suitable for the arid and semi-arid Loess Plateau regions.

Keywords Terraced land · Loess hill–gully area · Soil moisture and fertilizer · Improved GM(1,1) model · Agricultural ecology

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Introduction

The Loess Plateau of western China is ecologically frail and has received worldwide ecological concern (Tang et al. 1998; Wu et al. 2003; Hessel 2006). The Loess Plateau soils are highly erodible resulting in poor water and fertilizer conservation. Thus, appropriate land use in this area is important to maintain agricultural production and ecological environments. The local traditional land use was farming on the sloping land which promotes soil and water erosion during heavy rains. The associated agricultural practices have contributed to widespread land degradation (Shi and Shao 2000; Chen et al. 2007). Establishing sustainable agriculture in the Loess Plateau requires appropriate management to minimize soil and water erosion

(Li 2000). In the semiarid northwest Loess Plateau, the primary conservation and management practice is terracing which increases rainfall infiltration and fertilizer conservation, and reduces erosion (Lu et al. 2009; Shi and Shao 2000; Chen et al. 2007; Li 2000).

The Loess Plateau of Northwestern China has one of the highest erosion rates in the world. Here, the sloping farmland accounts for 50% of the total farmland, and 70–90% of the Loess hill–gully area (Tang et al. 1998) which is semi-arid with rapid water runoff and soil erosion. Terracing has become an effective measure to control surface runoff, preventing soil and water losses. Terracing changes the condition for crop growth for the fact that the runoff is prevented and the available water and heat is better utilized. Terracing also increases the moisture and nutrient use efficiencies (Li et al. 1994) which effectively enhances crop endurance to droughts and diseases and consequently increases crop yield. Accordingly, terracing can not only change the landscape, but also improves the local agricultural environment and the carrying capacity of the land.

A number of factors may influence the water and soil loss in the Loess Plateau. Hessel (2006) pointed out that the high sediment concentration in the runoff water is a characteristic feature of the Loess Plateau. It is probably caused by the erodible materials on steep slopes, the characteristics of the loess, and the harsh climate that results in low plant cover. Terracing changes the slope gradient, shortens the slope length, and thus clearly alters the pattern of water and soil conservation. Terracing is now the primary and standard measure to prevent soil and water losses in the Loess hilly–gully regions of China. Previous studies of the terraced land have mainly focused on the single index, either soil moisture or soil fertilizer. After terracing, the soil can retain rainfall of up to 100–200 mm in a single rain event without causing surface runoff (Zhao 1983). Furthermore, water erosion rates on the terraces are very low, generally less than 1 kg m^{-2} $year^{-1}$, unless the slope tangents exceed 0.1 (Quine et al. 1999a, b).

Jiao et al. (1999) analyzed the water and soil retention capacities of terraces in the Loess Plateau under different rainfall conditions. Results indicated that if the rainfall index Pi_{30} [calculated as rainfall (P) multiplies the maximum 30-min rainfall intensity] is less than 4.4 mm^2/min while $i_{30} < 0.28$ mm/min, the level terrace cannot reach its full water holding capacity. When Pi_{30} varies between 4.4 and 50 mm^2/min while $i_{30} > 0.28$ mm/min, the terrace's water and soil retention rate is 100%; and when $Pi_{30} > 50$ mm^2/min and $i_{30} > 0.28$ mm/min, water and soil retention decreases with increasing Pi_{30}. In the loess Plateau, water and soil loss is generally more sensitive to slope gradient and slope length, and the slope gradient is more readily causing runoff and erosion (Zhang et al. 1999).

Comparing two slopes at 14°40′ and of 28°52′ in the study of Jiao et al. (1999), the annual runoff volume ratio was 1:1.4; it is 1:2.52 with wash loads (eroded soil included). The ratios for the single rainstorm event would be 1:2.27 without wash loads and 1:2.12 with wash loads. When the length of the slope is increased by 40–67%, the annual runoff volume is increased by 2–3% without wash loads and 26–50% with wash loads; for single rainstorm events, the runoff volume is increased by 18–21% without wash loads, 49–55% with wash loads. The test also showed that for a single rainfall event of 95 mm, with an average rainfall intensity of 0.075 mm/min and maximal intensity of 1.2 mm, the terrace water retention rate is 92%. If a rainfall event of 150 mm has an average intensity of 0.075 mm/min, there is no water or soil loss from the terrace, and when it rains for 20 consecutive days, giving a total of 131.2 mm, the loss rate of water and soil is only 1.0%. Therefore, there is profoundly more soil moisture retained in the terraced land than in sloping land. In the newly built terraces, water retention capacity increased by 26.2%, and in older terraces (more than 3 years old) the water retention increased by 59.5%.

According to our monitoring in the Yulingou watershed of Zhuanglang county, Gansu province, during one rainfall event with a total precipitation of 101.4 mm and mean intensity of 23.1 mm/h, the sloping land generated a runoff volume of 247.5–452 m^3/ha and 57–124.5 t/ha of soil wash load; the terraced land did not produce any runoff. This indicates that terracing has profound effect on the water and soil retention in the loess hilly and gully areas (also see Paningbatan et al. 1995; Quine et al. 1999a, b; Dijk and Bruijnzeel 2003).

Meanwhile, the level terraces clearly retain nutrients. Following the terracing of sloping land, the first year crop yield may be reduced, but soil improvement and nutrient accumulation can be accelerated by fertilizing. Tests in the same terraced lot of Jiao et al. (1999) showed that the total nitrogen and organic content increased by 150 and 78%, respectively, in 20 years from 1961 to 1981. Between 1961 and 1964, the average total nitrogen and organic content in the terraced lots were, respectively, 33 and 25% higher than that on the sloping land. After 1964, the older terraced lands, the total nitrogen increased by 76.5%, the total phosphorus by 10% and the organic matter increased by 87%. Another field test (Chen 2001) in Zhuanglang County of Gansu Province showed more advantages of the terraced land. In a new terrace, the fast acting nutrients content was 0.38–9.74% higher than in the sloping land, the crop evapotranspiration was 14.9% higher and the average crop yield was 20.7% higher. In the older terraces (>3 years), there are greater increases in nutrient content, soil moisture and crop yield. The whole County's average crop yield from the terraced fields was 2,430 kg/ha in the period

1992–1997, which may account for 34% of the yield potential from precipitation. In the sloping farmland, the average yield was only 1391 kg/ha, accounting for about 18% of the yield potential from precipitation. The year 1997 was a dry year (50-year return period) with sever droughts and expectations for low crop yield. However, the average crop yield from the terraced fields reached 2,292 kg/ha, which is 12% higher than the average yield (2,010 kg/ha) of 1992, a normal hydrologic year. The average yield from the sloping land was only 1,080 kg/ha which is 25% less than 1,444.0 kg/ha in 1992. This clearly shows that the terraced land can not only conserve more precipitation water, but also supply the moisture continuously through the dry year, so that the crop yield is better guaranteed.

Nevertheless, the dynamics of moisture content, water conservation and soil fertilizer efficiencies of the terraced and slopping lands are not yet fully understood, particularly regarding the variation of moisture and its movement at different depths. In addition, the variation of soil moisture and fertilizer dynamics in the old terraced lands has not been fully examined. Further studies are also needed to understand the integrated effects of moisture and fertilizer increase on the ecological environment of the Loess Plateau.

To decipher the complicated interactions between soil moisture and soil fertilizer, improved Grey System Model (GSM) has been widely applied in the field for prediction and decision making due to its lower requirement for original data and high precision (Peng and Kirk 1999; Hsu and Wen 2000; Zhang and Li 2002). It is a relatively fast and effective means of studying the effects of terrace water storage.

The objectives of this study are to experimentally investigate the detailed processes controlling: (1) the changes in soil moisture and nutrients through vertical loess profiles in terraced versus sloping land; (2) crop production potentials of the terraced versus sloping land, and (3) the agricultural and ecological environments of the terraced versus sloping land. The grey system model was used to simulate the meteorological conditions for better crop yield.

Materials and methods

Descriptions of the study area

The study area is located in the western part of the Loess Plateau (35°03′23″–35°28′26″, 105°46′15″–106°23′45″) at altitudes varying between 1,400 and 2,587.5 m. The soil is sandy loam of loess origin. The climate is semiarid with the mean annual precipitation of about 547 mm. Nearly 60% of the annual rainfall is received between July and September. The mean annual temperature is 7.9°C with a maximum of 25°C (July) and a minimum of −10.6°C (January). The average annual potential evaporation is 1,310.2 mm.

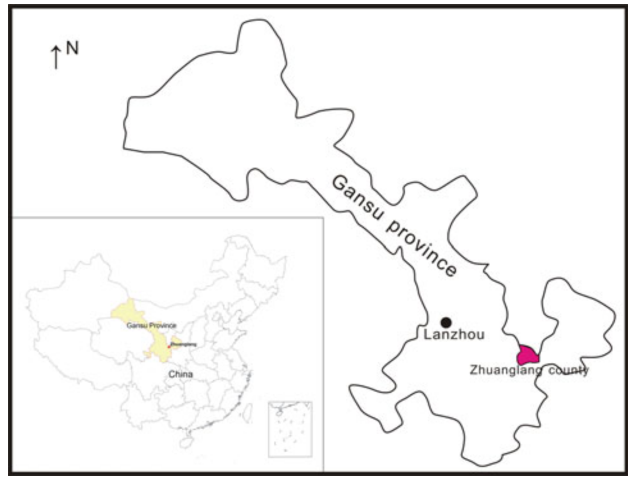

Fig. 1 Location of the study area of the Zhuanglang County in China

Zhuanglang County is located in the middle of Gansu Province (Fig. 1) and covers about 1,550 km^2. It belongs to the third sub-region in the loess hilly–gully area. Land with a slope below 5° covers about 8.6% of the area. Land with slope between 5° and 15° covers about 14.9, 46.6% for land between 15° and 25°, 16.1% for steep land between 25° and 35°, and 13.3% for extremely steep land with slope over 35°. The density of population in 2003 was 204 persons per square kilometers.

Construction of large-scale terracing across the entire County started in the 1960s, and by 1997 the total area of terraced fields reached 62,998 ha, accounting for 91.74% of the sloping land of the County (with slopes greater than 25°). The high-quality terraces cover about 53,546 ha, or 82% of the terraced fields (Yue 1998). In 1998 almost the entire County was terraced. The terraced fields account for 95% of the total arable land. After terracing, the local output of crops clearly increased.

Experimental design

Field experiments were designed and conducted on both the terraced and sloping lands in the local villages called Yulingou Valley and Hezhuangping of Zhanglang County (Fig. 2). The widths of the terraces are generally in the range of 2–10 m. Some of the terraces are used as tree plant orchards, while others are used to grow annual crops (e.g. wheat, potatoes, and corn).

Fore terraced fields were selected in the two villages. Each field contains three plots. Thus, a total of 12 terraced plots were used for the experiment. On the sloping land, ten plots were selected on natural slopes varying between 10°

Fig. 2 Location of the study area in the Zhuanglang County

and 25°. All of the sloped lands were facing southeast and planted with wheat.

According to the distribution depth of crops roots, we measured soil moisture at multiple depths 0–20, 20–40, 40–60, 60–80, 80–100 and 100–200 cm in the terrace land. In the sloping land, measurements were done at shallower depths 0–20, 20–40, 40–60 cm due to limited moisture penetration. Soil samples were obtained by extracting a 200 cm long core at each sampling location. From this core, three 30–50 g replicate soil samples were taken from each depth. Soil organic matter content, total N, total P, bio-available N and P were also measured from each sample.

The soil–water content was determined using the oven-drying method. Samples were pre-weighed, dried in the oven for 24 h at 105°C, then weighed again. The difference between the moist and oven-dry weights is the weight of water contained in the soil. The percentage weight of the soil samples is presented in Tables 1, 2, 3.

In addition, we gathered information on crop production in the slopping land and the terraced lands of different ages (see Table 4), as well as other County statistics from the Center of Agricultural Experiment Station of Zhuanglang County.

The experiments started on 1 March 2001 and ended on 16 September 2005. Samples were taken twice a month on the 1st and 16th day of the month throughout the study period.

Numerical modeling

In dryland farming of wheat and potato, the main crops of Zhuanglang County, precipitation, especially the infiltrated effective precipitation, is the most important factor impacting crop yield. A quantitative correlation between precipitation and potential crop yield is important for estimating the water use efficiencies. Thus, we conducted grey system modeling using the improved GM(1,1) model to simulate the correlation between crop yields and precipitation.

Grey system theory has been applied widely in engineering and management (Peng and Kirk 1999; Hsu and Wen 2000; Zhang and Li 2002). Because in Zhuanglang County the factors influencing crop production are many and complex, both the input factors and outputs all pertain the grey system characteristics (Deng 1992; Wang and Li 1999). The improved GM(1,1) model can be to simulate the efficiency of meteorological conditions for crop yields. Generally in the dry land farming areas of the loess plateau, effective rainfall or soil moisture is a main factor controlling the crop outputs while other conditions, such as fertilization, mechanization and cultivation techniques, are kept steady or improving (Chen 2001). The crop output can be divided into two parts according the model (Wang and Li 1999):

$$X = X_1 + X_2 \tag{1}$$

where X is crop output, X_1 is called trending output, or agricultural productivity due to improvements of agricultural techniques, X_2 is called meteorological output, reflecting effects of precipitation, temperature, sun light and hazardous weather conditions such as hailstorm and frost which occur regularly in Zhuanglang County.

Following is the modeling procedure of the improved Grey GM(1,1), an original factor series is assumed to be (Wang and Li 1999):

Table 1 The variation of soil moisture in sloping fields and terraced fields at 0–60 cm deep (%)

Month	Terraced fields (%)			Sloping fields (%)			Terraced fields increased (%)		
	0–20 (cm)	20–40 (cm)	40–60 (cm)	0–20 (cm)	20–40 (cm)	40–60 (cm)	0–20 (cm)	20–40 (cm)	40–60 (cm)
3	16.22	18.22	13.99	17.15	18.09	13.73	−4.8	0.72	1.89
4	21.31	20.34	17.96	19.81	18.00	16.92	7.57	13.00	6.15
5	14.31	18.17	16.05	14.13	17.31	16.11	1.28	4.96	0.37
6	19.51	19.19	18.43	19.06	18.48	18.21	2.57	3.8	1.2
7	8.00	9.75	10.07	6.70	8.79	8.91	19.40	10.92	13.02
Average	15.87	17.13	15.13	15.37	16.13	14.78	5.2	6.68	4.53

Table 2 The vertical change of soil moisture (%) in terraced land

Month	0–40 cm	40–100 cm	100–200 cm
4	11.61	11.20	15.59
5	11.38	13.80	14.88
6	10.92	11.56	13.44
7	13.62	12.80	15.50
Coefficient of variation (%)	10.06	9.66	6.69

Table 3 Winter wheat soil moisture (%) variations in terraced land

Month	0–20 cm	20–40 cm	40–60 cm	60–80 cm	80–100 cm	100–200 cm
4	11.49	11.73	10.46	11.17	11.96	15.59
5	12.11	10.64	11.06	13.32	17.03	14.88
6	10.32	11.51	12.84	11.47	10.38	13.44
7	12.69	14.55	12.77	12.64	12.99	15.50

$$X^{(0)}(k) = \left\{x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n)\right\}, \tag{2}$$

where $x^{(0)}(i)$ corresponds to the output at time i.

The accumulated generating operation (AGO) formation of $x^{(0)}$ is

$$X^{(1)}(k) = \left\{x^{(1)}(1), x^{(1)}(2), \ldots, x^{(1)}(n)\right\}, \tag{3}$$

where $x^{(1)}(k) = \sum_{i-1}^{k} x^{(0)}(i), \quad k = 1, 2, \ldots, n.$

From Eq. 2, the following first order differential equation can be formed:

$$\frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = u, \quad t \in [0, \infty), \tag{4}$$

where $\frac{dx(t)^{(1)}}{dt}$ is the grey differential coefficient of series, a, u are parameters to be estimated. In order to estimate the parameters a and u, Eq. 4 is expressed as (integral over [k, $k + 1$] to replace $x^{(1)}(t)$ in Eq. 4)

$$x^{(0)}(k+1) = -az^{(1)}(k+1) + u \quad k = 1, 2, \ldots, n-1, \tag{5}$$

where $z^{(1)}(k)$ is the background value which is defined as

$$z^{(1)}(k) = \frac{x^{(1)}(k+1) - x^{(1)}(k)}{\ln^{(1)}(k+1) - \ln^{(1)}(k)}.$$

Table 4 Crop production in terraced land constructed in different years

Terraced field age	Average output (kg/ha)	Increased Output relative to 10° sloping fields (kg/ha)	Increased rate relative to 10° sloping fields (%)
The first year	2,935.05	102.0	3.60
3 years' construction	3,600.0	766.95	27.07
5 years' construction	3,833.4	1,000.35	35.31
7 years' construction	4,328.4	1,495.35	52.78
Sloping fields with 10° up	2,833.05		

The parameter vector $\hat{a}$ can be estimated using the least-square method, i.e.

$$\hat{a} = \left[B^{T}B\right]^{-1}B^{T}y_n, \tag{6}$$

where $\hat{a} = [a, u]^{T}, y_n = \left[x^{(0)}(2), x^{(0)}(3), \ldots, x^{(0)}(n)\right]^{T}$ and

$$B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \ldots & \ldots \\ -z^{(1)}(n) & 1 \end{bmatrix}.$$

The solution of Eq. 4 can be obtained after the parameter vector $\hat{a}$ (Eq. 6) is estimated.

Obtaining the estimate of $x^{(1)}(t)$, while assuming $x^{(1)}(t)|_{t=1} = x^{(0)}(1)$ leads to

$$\hat{x}^{(1)}(t) = \left[x^{(0)}(1) - \frac{u}{a}\right]e^{-a(t-1)} + \frac{u}{a} \tag{7}$$

$$\text{and } \hat{x}^{(1)}(k+1) = \left[x^{(0)}(1) - \frac{u}{a}\right]e^{-ak} + \frac{u}{a}. \tag{8}$$

Applying inverse accumulated generating operation (IAGO) to Eq. 9 leads to:

$$\begin{cases} \hat{x}^{(0)}(1) = x^{(0)}(1), \quad k = 1; \\ \hat{x}^{(0)}(k+1) = \hat{x}^{(1)}(k+1) - \hat{x}^{(1)}(k) = (1 - e^{a})\left[x^{(0)}(1) - \frac{u}{a}\right]e^{-ak} \end{cases} \quad k = 1, 2, \ldots, n-1. \tag{9}$$

Since 1992, the Zhuanglang County gradually implemented the dryland farming agricultural techniques entirely. These output data comply with the request of the improved GM(1,1) model. Thus, applying Eqs. 2–9 to data of annual output of winter wheat and potato, respectively, of Zhuanglang County from 1992 to 2005, one can calculate and obtain X_1 and X_2. The results are shown in Table 5.

According to the results of numerical modeling (Table 5), the X_2 values of Annual Winter wheat output and

Table 5 Crops' meteorological output of winter wheat and potato

Year	Annual winter wheat output (kg/ha)			Annual potato output (kg/ha)		
	X	X_1	X_2	X	X_1	X_2
1992	1,614.5	1,614.5	0	2,039.905	2,039.90	0
1993	1,985.9	1,584.7	401.20	2,099.90	2,262.64	−162.76
1994	1,721.95	1,630.3	91.60	2,054.90	2,334.58	−279.68
1995	1,140.84	1,677.31	−536.47	2,129.90	2,408.81	−278.91
1996	1,779.64	1,725.63	54.01	2,849.86	2,485.40	364.46
1997	1,803.84	1,775.34	28.50	2,369.88	2,564.42	−194.53
1998	1,915.51	1,826.48	89.02	3,104.84	2,645.96	458.88
1999	1,566.46	1,879.10	−312.64	3,014.85	2,730.08	284.76
2000	1,408.46	1,933.23	−524.77	3,389.83	2,816.89	572.9
2001	2,230.27	1,988.92	241.35	2,624.86	2,906.45	−281.58
2002	2,366.11	2,046.22	319.89	2,444.87	2,998.86	−553.98
2003	2,258.49	2,105.16	153.32	2,369.88	3,094.21	−724.33
2004	2,345.02	2,165.81	179.19	2,460.01	3,192.59	−732.59
2005	2,526.01	2,228.20	297.80	2,534.21	3,294.10	−760.10

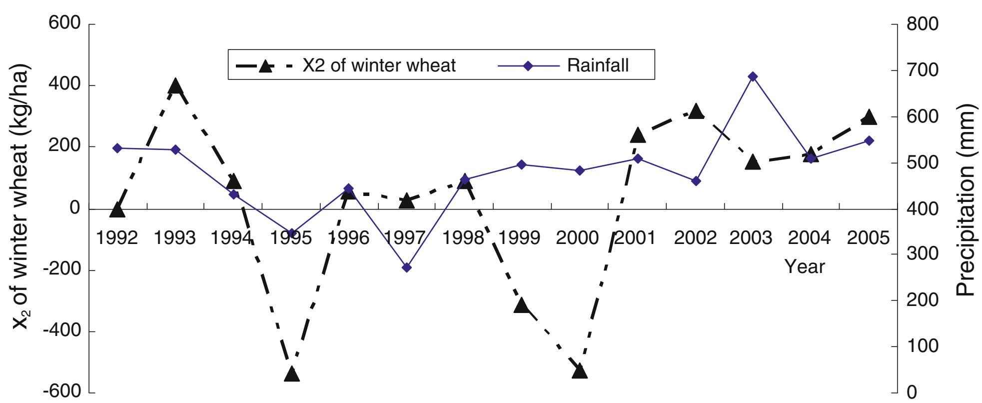

Fig. 3 Relationship between X_2 of winter wheat and precipitation (1992–2005) in Zhuanglang

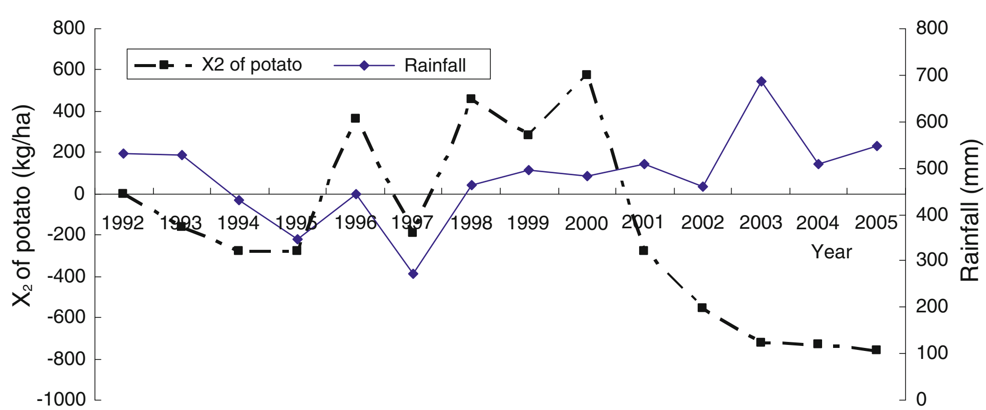

Fig. 4 Relationship between X_2 of potato and the precipitation (1992–2005) in Zhuanglang

Annual Potato output before the year of 1998 all have high relevance with rainfall, but after this time the relevance decreased gradually (Figs. 3, 4). By correlation analysis of winter wheat output and potato output during 1992–1998, the correlation coefficient are 0.618, 0.435, respectively, The results explain that the crop water requirement during the growing period (from March to June) is mainly derived from the deep storage of soil moisture. The main reason is that the terrace can increase the moisture storage and the production of crops in this area.

The above results also explain that the potato is more drought-resistant than winter wheat, and it is more suitable for this region. It is indeed a reality that in recent years, the potato growing area is rapidly increasing and it has become a high-quality specialty crop from this region.

Results and discussion

According to the monitoring results, terraces built within 1 year contain more soil moisture than the sloping land. Water conservation in the terraces increased continuously over the years mainly within the top 60 cm of soil. Compared to the sloping land, the top 60-cm water conservation increased by 9.15–46.41 mm, representing an average moisture content increase of 8.9–14.45% (maximum being 46.1%) during the crop growing period (Table 1).

Field monitoring indicated that the land type, direction of slope and land use type can influence the soil moisture conservation. Land use type (terracing or not) plays an important role in water conservation, causing the major differences in crop growth that are most markedly shown in the root growth. In sloping land, crop roots are superficial, and absorb only shallow water at depths less than 40 cm. Their consumption of shallow water is 6.6–7.7 mm more than in the terraced land. However, in the terraced fields where the crop root is deeper, water consumption at depths of 40–180 cm was 41.3–46.4 mm more than in the sloping land. Additionally, during the growing period, crops in terraces can absorb more water than in sloping land, thus increasing the uptake of deep moisture and reducing evaporation losses.

The monitoring study also indicated that during the study period of 3 years when more terraces were constructed, the soil fertility in the terraces has increased while the soil moisture remained relatively steady. Compared with a 15° slope the soil organic content of the terraced land increased by 26%, total N by 8%, total P by 4%, fast acting N by 12%, and fast acting P by 20%. Based on the 3-year continuous investigation in He Zhuangping village of Zhuanglang County and compared with sloping land with slope greater than 10°, crop production from the terraces (older than 3 years) was 27% higher. Additionally, with increase in the age of the terraces in the first 3 years, the crop production increased by 27.07 to 52.78% (Table 4).

The above monitoring and planting tests show that terracing creates better conditions for water and nutrient conservation than the sloping land, especially in the 40–180 cm depths. The crops can effectively use them during the dry season, thus terracing creates much more favorable conditions for crop growth.

As shown in Table 2, the vertical soil moisture changes can be divided into three layers. The top activity layer between 0 and 40 cm is influenced directly by weather and

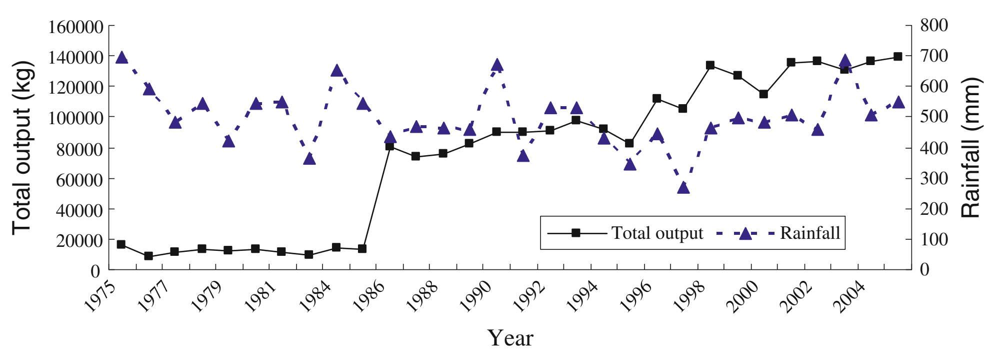

Fig. 5 The change in total crop yield and Rainfall during 1975–2005 in Zhuanglang

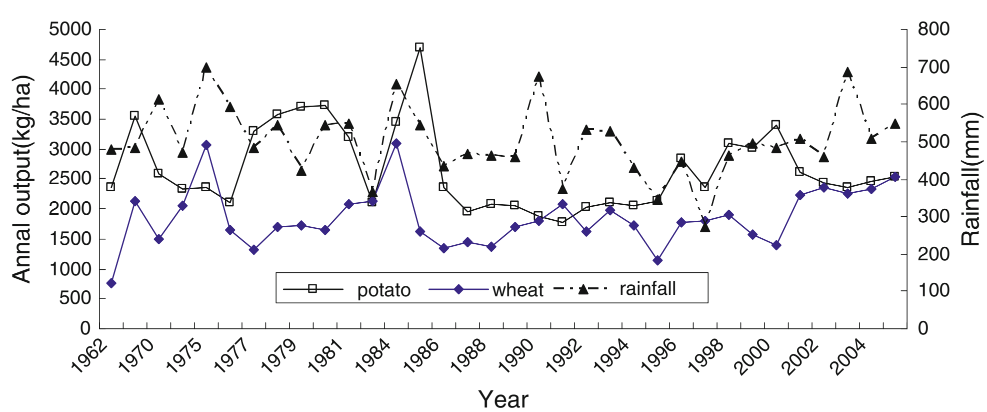

Fig. 6 The annual output of potato and winter wheat during 1949–2005

Table 6 Runoff modulus and erosion modulus of terraced fields in different periods

Year	1964–1969	1970–1980	1981–1992	1993–1997	1964–1997
Runoff (10^4 m^3)	418.32	8,764.8	10,185.76	3,120.8	61,652.4
Erosion (10^4 t)	43.3	907.2	1,054.3	323.0	6,381.33

Fig. 7 Zhuanglang's terraced view in the summer (2006)

anthropogenic factors. The soil moisture varies greatly, and in the crop growth period it changes from 10.92 to 13.62% with a coefficient of variation of 10.06%. The second layer between 40 and 100 cm below the surface shows a gradual change but wide variations in soil moisture. This layer is influenced by precipitation, evaporation and crop water absorption. Throughout the crop growing period the soil moisture in this layer changed from 11.56 to 13.80%, with a coefficient of variation is 9.66%. The third layer between 100 and 200 cm has small variations in soil moisture, showing that it is seldom influenced by weather and crop roots. In the entire crop growing period the soil moisture in these depths changed from 13.44 to 15.59%, with a coefficient of variation of 6.69%.

For winter wheat, the soil moisture in the terraced wheat field (Table 3) showed that during months from April to June there is a rapid loss of soil moisture in top 80 cm layer due to rising air temperature, low humidity and low precipitation. Not only the effective rainfall is low, this loss is enhanced by crop absorption. However, the moisture content rises again, particularly at 0–100 cm depths, after July with increasing amount of rainfall. In October before the soil is frozen, the soil moisture in the top 100-cm layer of the terraced lands increased by 290.85–403.3–487.26–415.29 m^3/ha as compared to the sloping lands at slopes of 10°–15°–20°–25°, respectively. Therefore, in order to maximize the winter wheat yield, it is very important to increase the water storage using autumn rainfall after harvesting in this area.

Variations in total crop yield (include wheat, potato, corn, benne and some medicinal plants) between 1975 and 2005 are shown in Fig. 5. This figure can be divided into three periods: (1) pre-1986 when the total yield was less than 20,000 t/year; (2) from 1986 to 1996 when the total yield increased rapidly and reached 80,000 t/year due to construction of terraces, favorable agricultural policy and climate; and (3) post-1997 with continued increase in crop production due to large-scale terracing in the entire County. During the second period from 1986 to 1997, Gao (2004) showed that in 22 towns and villages in the County, there was a mean profit of 45.3% from the construction of terraces.

Changes in crop yield are also controlled by local weather, particularly rainfall. Figure 5 shows the annual rainfall for Zhuanglang County during 1962–2005. It can be seen that the rainfall pattern showed marked changes but a general decreasing trend since 1962. However, the crop yield tend to increase, even during the drought of 1997 (50-year return period), showing that the influence of rainfall alone on crop yield is limited.

Table 7 Comparison of wheat yield from terraced fields with that of sloping fields in a similar area (kg/ha)

	1993	1994	1995	1996	1997	Average
Sloping fields	2,821.359	2,624.869	2,173.391	2,737.363	1,103.945	2,291.885
Terraced fields	3,448.328	3,269.837	2,968.352	3,607.32	2,291.885	3,116.844
Increase production per unit (kg/ha)	626.9687	644.9678	794.9603	869.9565	1,187.941	824.9588

Table 8 The net increase in production of wheat from 1993 to 1997

Year	1993	1994	1995	1996	1997	Sum
Effective increase production area (ha)	4,132.73	4,250.12	4,486.24	4,514.25	4,294.15	21,677.5
Net increase (10^4 kg)	2,589.9	2,740.0	3,564.8	3,925.4	5,098.9	17,919

Fig. 8 Potato planting pattern in the terraced land (2006)

In addition, the yields of the main crops (potato and wheat; Fig. 6) before and after terracing show wide variability before 1988, followed by more steady but slowly increasing yields since 1989. The smaller changes reflect annual variability in rainfall.

The above monitoring and computational results indicate that construction of terraces and implementation of water saving measures substantially increased crop yields and help guarantee food production in the County.

Ecological benefit

According to previous research, the runoff modulus of the sloping land in the loess plateau is about 679 m^3/ha a, and the erosion modulus is about 69.96 t/ha a. However, in the terraced land, field measurements at Puzigou and Yulingou (both in Zhuanglang County) showed that the average runoff modulus was 15 m^3/ha a and the erosion modulus is 1.23 t/ha a. Thus, the runoff modulus was reduced to 2.2% and the erosion modulus reduced to 1.8%.

According to "The Water and Soil Conservation Comprehensive Control and Benefit Analysis Method" (National Standard of the China 1995), we computed the ecosystem and economic benefit of terraced fields using the net benefit method. We also calculated the reduction in the runoff and erosion modulus for various periods. The results are shown in Table 6.

According to Table 6, from 1964 to 1997, the overall reduction in runoff in Zhuanglang County is 6.16×10^8 m^3, and the reduction in erosion is 6.381×10^7 t, both as a result of the terraced land construction. According to the benefit calculation this reduction has the equivalent benefit of 1.317×10^5 t of urea or 7.75×10^5 t of superphosphate. Assuming that the price of urea is 1.35 Yuan/kg and the price of superphosphate is 0.56 Yuan/kg, the increased fertility benefit is RMB Yuan 6.2×10^8. Since 1997, the terraced land of the whole County can trap and store 4.185×10^7 m^3 of water annually, and the rate of water storage is 86%. About 4.33 million tons of sediment is intercepted annually, and the retention rate is 97%. According to the water and soil conservation comprehensive control and benefit analysis method, if the intercepting sediment is worth 1 Yuan/t and stored water worth 0.08 Yuan/m^3, then the total benefit of intercepting sediment and water is 7.678 million Yuans in the about 68,666 ha of terraced fields in Zhuanglang County. By the end of 1997, the intercepted sediment and stored water increased by a factor of 1.3 relative to 1992, which accounted for 78 and 66% of the whole County's capacity for intercepting sediment and water from terracing. This terraced land has controlled the soil erosion most effectively while raising soil's water content and fertility.

Before 1993, the forest and grassland coverage was 186 km^2 (or 12%) in Zhuanglang County, but terracing and furrow planting have increased this coverage to 281.09 km^2 (18.1%) in 1997, and 35.1% in 2005 (Fig. 7).

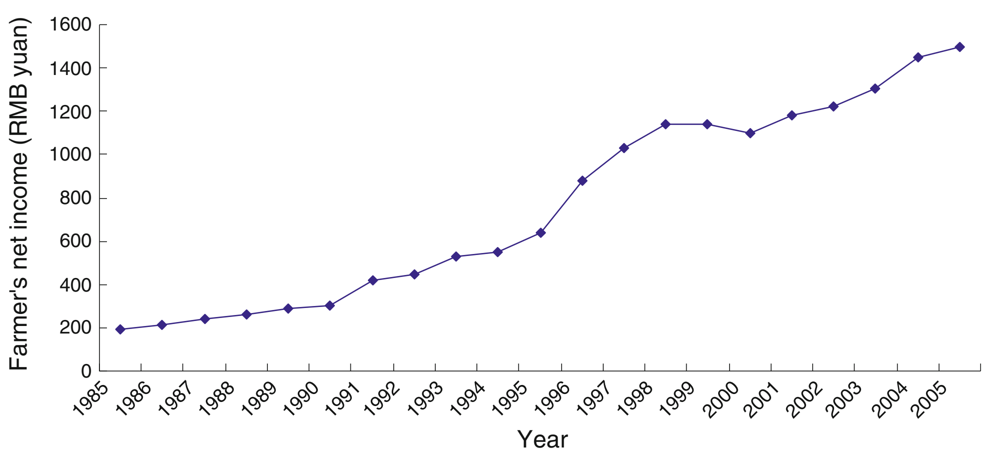

Fig. 9 Farmer's income per capita (Yuan) during 1985–2005

Economic benefit analysis

Using data on the wheat yield per unit area between 1993 and 1997 in Zhuanglang County, we calculated the yield of the terraced land and sloping land in similar areas, as shown in Table 7. The net increase in production is given in Table 8. These figures indicate that the average yield per unit area from the terraces is 824.96 kg/ha more than that from sloping land between 1993 and 1997. Despite the drought of 1997, the increase in production is the greatest, up to 1187.94 kg/ha, which further highlights the benefits of terraced land in the arid area.

In Zhuanglang County, the construction of terraces and increased application of science and technology have changed the agricultural industry substantially, which helped provide a solid base for future development. The crops have seen further improved by introducing better varieties, machine sowing, corn germination under plastic, and pit-grown potatoes under plastic covers (Fig. 8). Up to 2006, 4,000 ha of fruits, 666.67 ha of vegetables and 10,000 ha of merchandised potato have been established on terraces. Fruits, starch, grass and pork had formed the four major pillar industries. Furthermore, farmer's income has grown notably following the construction of terraces (Fig. 9), attaining 1,550 Yuans per capita in 2005.

According to the development index of Gansu Province (Chen 2001), the population carrying capacity of the land has increased from 195 people/km^2 before terracing in Zhuanglang County to 315 people/km^2 after terracing. The population carrying capacity of the economy was raised from 198 to 499 people/km^2. Equivalent figures for the loess plateau are: the population carrying capacity was increased from 148 to 374 people/km^2. This shows that the carrying capacity of the land has increased continuously following the land terracing in Zhuanglang County.

Conclusions

The calculated results are in good agreement with experimental data, both field test and Grey model (GM) calculation show that the terraced land in the agricultural areas of the Loess Plateau tends to store and retain more water, and promote more favorable interaction of water and fertilizer, relative to sloping land. In the Loess Plateau, water scarcity makes conservation extremely important, and developing sustainable agriculture requires implementing water conservation practices. This works fully show that terrace is the primary conservation management.

Terraced fields are important for the engineering of water and soil conservation in hilly–gully loess plateau areas in arid and semi-arid regions. Terracing results show remarkable increases in soil moisture storage and soil fertility, especially in the 40–180 cm depth. So, during the dry season, crops can absorb more water than in sloping land, thus increasing the uptake of deep moisture and reducing evaporation losses.

From the drought year 1997s crops output show that terracing has markedly increased the ability of the land to moderate the effects of natural hazards such as prolonged drought on crop yield, to reduce water and soil loss, and also increased more rainfall after harvesting in the autumn (rain season in local).

By the quantitative calculated results of the economic benefit and viewing the economic development of Zhuanglang County over the past 10 years, construction of the terraced fields has profoundly altered eco-environment and established firmer and reliable agricultural bases. Along with the improvement of the agricultural environment, the land utilization rate and unit land productivity are greatly enhanced.

So terracing has improved the basic agricultural cultivation conditions and agricultural development efficiency, established a base for sustainable agricultural development in the future, and promoting local society and economic stability in Zhuanglang County. It also provides an example for agricultural development in other arid and semi-arid regions of the world.

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