# Using Cs-137 measurements and reservoir deposits to investigate the effects of ceasing cultivation on sediment yields and sediment sources in a small catchment on the Loess Plateau of China

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**Abstract** The impact of ceasing cultivation on specific sediment yields and relative sediment contributions from the gully and inter-gully areas within a small catchment in the Rolling Loess Plateau of China has been examined by comparing the volume and $^{137}Cs$ content of sediments deposited in a reservoir before and after 1993. It is suggested that compaction of the formerly ploughed soils caused their erosion resistance to increase but reduced infiltration rates. Rates of soil loss from the inter gully areas therefore decreased but runoff increased. Increased runoff caused increased erosional activity within the receiving gully areas and an increase in the total sediment yield from the catchment.

**Key words** ceasing cultivation; China; $^{137}Cs$ measurements; reservoir deposits; Rolling Loess Plateau; sediment sources; specific sediment yield

## INTRODUCTION

The Rolling Loess Plateau in Northern Shaanxi and Western Shanxi is one of the most eroded regions of the Loess Plateau of China. Specific sediment yields commonly exceed $1.0 \times 10^4$ t km$^{-2}$ year$^{-1}$. The rolling plateau can be divided into two main geomorphic units, namely, the gully areas and the inter-gully areas, which represent the rolling plateau surface. Sheet and rill erosion are widespread on the inter-gully areas, where the land has been extensively cultivated, while gully erosion and mass movements predominate in the gully areas. Relative sediment contributions from the inter-gully and gully areas are about 30% and 70%, respectively (Jiang *et al.*, 1990; Jing *et al.*, 1997). Since the "Closing cultivation for land rehabilitation" policy was introduced in the 1990s, cultivation has been stopped on much of the sloping cultivated land to promote large scale revegetation of the Loess Plateau. The impact of ceasing cultivation of the sloping lands needs to be assessed, in order to establish its effects on both the geomorphic evolution of the area and the reduction in sediment yield.

Within a previous study undertaken in 1993, the $^{137}Cs$ technique was used to assess erosion rates on the sloping cultivated land and the relative sediment contributions from the inter-gully and gully areas in the Zhaojia Gully catchment (Zhang *et al.*, 1997). Cultivation has gradually ceased on most of the cultivated land in the catchment since the 1990s. To examine the impact of this ceasing of cultivation, the catchment was visited in 2001 to collect samples of the sediment deposited in the reservoir between 1993 to 1996 for $^{137}Cs$ measurements. By comparing both the volume of the deposited sediment and its $^{137}Cs$ content before and after 1993, the changes in erosion rates and sediment yield have been assessed.

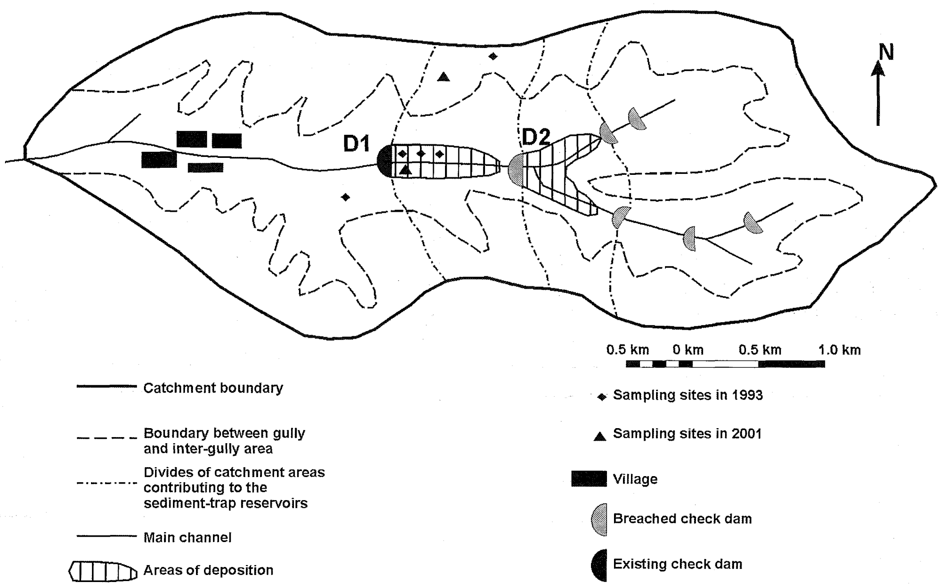


**Fig. 1** A sketch map of the Zhaojia Gully catchment and the sampling locations.

## THE STUDY CATCHMENT AND THE LAND-USE CHANGES

The Zhaojia Gully catchment is located 3 km east of Zichang Town, and constitutes a small tributary of the middle reaches of the Qingjian River which drains into the Yellow River. The catchment is underlain by loess deposits >100m thick and has a drainage area of 3.86 $km^2$, an average altitude of 1050 m and a relative relief of 300 m. The inter-gully area and gully areas account for 53 and 47% of the catchment area, respectively (Fig. 1). Sheet and rill erosion were previously widespread on the cultivated land of the relatively gentle inter-gully area with gradients <25°. The gully area consists mostly of steep gully slopes with gradients >30°. Gully erosion and mass movements are the major sediment sources in the gully area. The average annual precipitation is 513 mm, of which approximately 65% occurs during the flood season from July to September.

Land use conditions in the catchment in 1993 are shown in Table 1 (Zhang *et al.*, 1997). The land in the inter-gully area was almost entirely cultivated, and there were a few areas of steep cultivated land on the lower parts of gully slopes near Zhaojia Village in the lower reaches of the catchment. There is little terraced land in the catchment, although a few hectares of such land were constructed in the 1970s.

Several check dams have been constructed in the catchment since the 1970s to trap sediment as well as to create flat fertile farmland (Fig. 1). Dam 2, which is 12 m in height, was constructed in the middle reaches of the catchment in 1971 and had no overflow provision. It controlled an upstream drainage area of 2.03 $km^2$. Before the 1975 flood season, five small dams, 5–7 m in height and without spillways, were constructed upstream of Dam 2 and the upstream drainage area controlled by Dam 2 was reduced to 0.46 $km^2$. Unfortunately, those five small dams failed during the big floods of 4–5 July 1977 and Dam 2 was almost filled with sediment and the floodwater spilled over the dam. Subsequently, the crest of Dam 2 was gradually eroded by floodwaters and a narrow straight channel was incised into

**Table 1** Event rainfall, mean $^{137}Cs$ content of deposited sediment, specific sediment yield, and relative sediment contributions from the inter-gully area and from the gully area for the 13 flood couplets deposited during the period 1993–1996.

| Date | Rainfall (mm) | Mean $^{137}Cs$ content (Bq kg$^{-1}$) | Relative sediment contribution from the gully area (%) | Relative sediment contribution from the inter-gully area (%) | Specific sediment yield (t km$^{-2}$) |
|---|---|---|---|---|---|
| 8–10 August 1996 | 44.6 | 0.48 | 85 | 15 | 6537 |
| 1 August 1996 | 53.9 | 0.18 | 94 | 6 | 10866 |
| 7–16 July 1996 | 52.2 | 0.72 | 78 | 22 | 3782 |
| 26–28 June 1996 | 29.1 | 0.00 | 100 | 0 | 1205 |
| 15–18 June 1996 | 94.7 | 0.00 | 100 | 0 | 21437 |
| 29–31 August 1995 | 56.2 | 0.79 | 76 | 24 | 10645 |
| 25–28 August 1995 | 58.3 | 0.00 | 100 | 0 | 8627 |
| 5–6 August 1995 | 58.6 | 0.73 | 78 | 22 | 6973 |
| 17–18 July 1995 | 61.0 | 0.42 | 87 | 13 | 8796 |
| 31 August 1994 | 78.7 | 0.81 | 75 | 25 | 37816 |
| 10–12 August 1994 | 47.1 | 0.64 | 80 | 20 | 5902 |
| 7–8 July 1994 | 41.1 | 0.20 | 94 | 6 | 2861 |
| 19–23 August 1993 | 48.8 | 0.73 | 78 | 22 | 2720 |

the sediment deposited behind the dam, until it reached the bed of the former gully. Dam 1 was constructed 450 m downstream of Dam 2 before the 1988 flood season and it controls an upstream drainage of 2.63 km$^2$. It is an earth dam 23 m in height, which incorporates both a side spillway and a bottom culvert with several intakes. The total storage capacity of the reservoir was $0.5 \times 10^6$ m$^3$ and the impounded floodwater was used for downstream irrigation. In order to maintain the storage capacity for large floods, floodwater has been released through the intakes and bottom culvert during the floods that occurred since 1997. During the five dry years between 1997 and 2001, no major floods occurred and all the incoming sediment load was discharged through the open intakes and the bottom culvert and very little sediment was deposited in the reservoir. The cultivated land on the rolling plateau surface area has been gradually abandoned since the early 1990s. A survey undertaken in 2001 showed that nearly all the sloping cultivated land in the catchment had been abandoned by 1995, except for a few areas of sloping cultivated land close to the villages. Overgrazing was widespread in the catchment prior to cessation of cultivation. Grazing has now also been prohibited and the vegetation cover has shown significant recovery, although tree planting has proved unsuccessful.

## FIELD SAMPLING AND LABORATORY MEASUREMENTS

In order to assess erosion rates on the sloping cultivated land and the relative sediment contributions from the inter-gully area and the gully area, the sediment deposited within the sediment-trap reservoirs and the soils of the catchment were sampled in October 1993 (Fig. 1) (Zhang *et al.*, 1997). A $^{137}Cs$ reference profile was collected from the grassland surrounding an old tomb on the rolling plateau surface using a special corer. The sampling depth was 35 cm. The sampling method for cultivated soil profiles was the same as for the reference profile. Samples of surface soil (<5 cm) were also collected. A profile of the sediment deposited in the reservoir behind Dam 1 by the 1993 floods was collected using a corer. A profile of the sediment deposited by the floods occurring from 1973 to 1977 was collected from the wall of the channel incised into the sediment deposited behind Dam 2. All sediment deposit profiles were carefully sectioned to reflect flood deposit cycles and each couplet was usually subdivided into three samples. A few thin couplets were divided into two samples.

In order to establish the impact of ceasing cultivation of the sloping land in the catchment on soil erosion and sediment yield, a pit 9.2 m in depth with a diameter of 1 m was dug 50 m upstream of Dam 1 in November 2001, to collect a profile of the sediment deposited in the reservoir from 1993 to 1996. Depth incremental samples of the profile were collected from the side of the pit, taking account of the flood cycles. Each couplet was subdivided into at least three samples. In addition, five soil profiles for measurement of the $^{137}$Cs reference inventory were collected from the 1993 reference sampling site, using the same procedure as in 1993.

All samples were air-dried, disaggregated and passed through a 2 mm sieve prior to analysis of their $^{137}$Cs activity by gamma spectrometry using an HPGe detector. The counting times, which were typically about 55 000 s, provided results with an analytical precision of approximately ±6% at the 95% confidence level.

## SEDIMENT YIELDS AND RELATIVE CONTRIBUTIONS FROM THE GULLY AND INTER-GULLY AND INTER-GULLY AREAS BEFORE 1993

The main findings of the 1993 investigation of soil erosion and sediment sources in Zhaojia Gully reported by Zhang *et al.* (1997) are as follows:

(a) In the inter-gully area, cultivated land on the gentle hill summits and the steeper hillslopes account for 14% and 36% of the catchment area, respectively, while grass land only accounts for 3%. In the gully area, grass slopes, bare slopes and steep sloping cultivated land account for 21%, 19% and 2% of the catchment area, respectively, while other types of land, such as channels, terrace land and villages account for 5%.

(b) The local $^{137}$Cs reference inventory was 2500 Bq m$^{-2}$. The average $^{137}$Cs content of the cultivated soils in the inter-gully area was 3.9 Bq kg$^{-1}$, while the surface soils on bare slopes and areas affected by mass movements contain little $^{137}$Cs (0.02 Bq kg$^{-1}$).

(c) 1993 was a dry year with an annual precipitation of 429.8 mm and the catchment had a specific sediment yield of 4627 t km$^{-2}$ year$^{-1}$. The average $^{137}$Cs content of the sediment deposited by two floods was 0.74 Bq kg$^{-1}$ and 1.06 Bq kg$^{-1}$, respectively. Based on these values and the values listed above for the $^{137}$Cs content of the potential sources, the mean relative sediment contributions from the inter-gully area and the gully area in 1993 were estimated to be 26.9% and 73.1%, respectively.

(d) The years from 1973 to 1977 were a wet period and the annual precipitation varied between 513.0 mm and 670.3 mm, with a mean value of 521.8 mm. Fifteen floods occurred during this period and the mean specific sediment yield was 16 291 t km$^{-2}$ year$^{-1}$. The sediment deposits associated with four flood events occurring in the early part of the wet season had a $^{137}$Cs content of <1.0 Bq kg$^{-1}$, indicating that nearly all the sediment mobilized by those events was derived from the gully area and that the relative sediment contribution from the gully area was >85%, with the maximum contribution reaching 98.6%. For the other 11 flood events, the $^{137}$Cs content of deposited sediment varied between 1.12 and 1.15 Bq kg$^{-1}$, and the relative contributions from the gully area varied between 67.0% and 82.5%. The mean specific sediment yield from the catchment for this period was 13 413 t km$^{-2}$ year$^{-1}$ and the equivalent yields for the inter-gully area and the gully area were 6580 t km$^{-2}$ year$^{-1}$, and 21 118 t km$^{-2}$ year$^{-1}$, respectively. The relative sediment contributions from the inter-gully area and the gully area were estimated to be 26% and 74%, respectively.

## CHANGES IN SEDIMENT YIELD AND THE RELATIVE CONTRIBUTION OF SEDIMENT FROM THE INTER-GULLY AND GULLY AREAS SINCE 1993

Based on evidence provided by down-profile variations in grain size composition and the $^{137}$Cs content of the sediment, the rainfall records data and information obtained from local farmers, the sediment profile collected from the pit dug in the reservoir of Dam 1, comprised 13 flood couplets (Fig. 2). The rainfall totals corresponding to these couplets are shown in Table 1.

A field survey undertaken in November 2001 indicated that the surface area of the sediment deposited in the reservoir basin of Dam 1 was 29 310 m$^2$, 6131 m$^2$ greater than the area of 1993. The total volume of sediment deposited between 1994 and 1996 was 167 101 m$^3$, of which the volume associated with the four floods associated with couplets 4, 7, 8, and 9 accounted for 62.6% of the total volume. The major flood of 31 August 1994 (Couplet 4) accounted for 30% of the total volume. Based on the volume of the sediment deposits and assuming a bulk density of 1.4 t m$^{-3}$, the specific sediment yields for 1994, 1995 and 1996

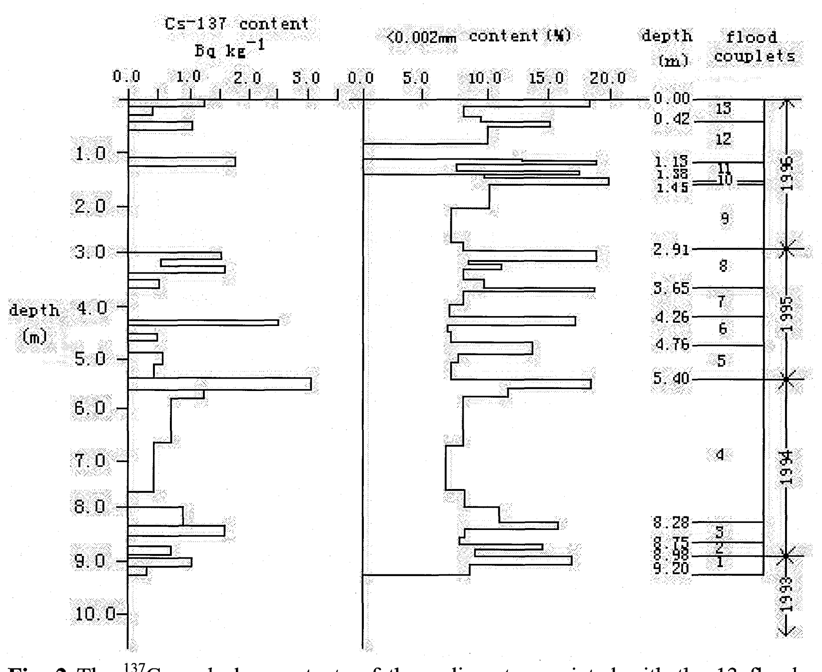


**Fig. 2** The $^{137}$Cs and clay contents of the sediment associated with the 13 flood couplets deposited between 1993 and 1996.

were calculated to be 33 034, 24 851 and 31 086 t km$^{-2}$ year$^{-1}$, respectively, and the mean value for the three years was 29 650 t km$^{-2}$ year$^{-1}$, which was 2.2 times greater than the average specific sediment yield of the catchment. It appears that cessation of cultivation on the sloping land of the rolling plateau surface did not result in a reduction of sediment yield from the catchment.

The mean $^{137}$Cs inventory of the five reference soil profiles collected in 2001 was 1966 Bq m$^{-2}$, a value very close to the value of 2076 Bq m$^{-2}$, equivalent to the reference inventory of 2500 Bq m$^{-2}$ measured in 1993 (Zhang *et al.*, 2003). The average annual $^{137}$Cs content of the sediment deposits from 1994 to 1996 ranged between 0.18 Bq kg$^{-1}$ and 0.75 Bq kg$^{-1}$ with a mean of 0.45 Bq kg$^{-1}$ (Table 2). The average $^{137}$Cs content of the 1993 sediment deposits, sampled in 1993, was 0.90 Bq kg$^{-1}$ (Zhang, 1997). Taking account of decay, this value would be 0.75 Bq kg$^{-1}$ in 2001, a value very close to 0.73 Bq kg$^{-1}$ which represents the average $^{137}$Cs content of the 1993 sediment deposits sampled in 2001. Since 1994, the average annual $^{137}$Cs content of the deposited sediment has declined markedly from 0.75 Bq kg$^{-1}$ in 1994 to 0.49 Bq kg$^{-1}$ in 1995, and 0.18 Bq kg$^{-1}$ in 1996. This sharp decline in the $^{137}$Cs content of the sediment deposited from 1994 to 1996 contrasts with the findings of the 1993 investigation which indicated that: "The limited variation in the mean $^{137}$Cs content of the sediment deposits for each year during the period of 1973–1977 indicated that the overall relative contributions of sediment from the rolling plateau and from the gully area remained fairly constant from year to year". It is clear that the relative sediment contribution from the gully area has increased, while that from the inter-gully area has decreased, since 1994 because sediment mobilized from the former area contains little $^{137}$Cs.

As in the previous study, the relative sediment contributions from the inter–gully area and the gully area have been estimated using a simple mixing model:

$$Cd = Cm \times fm + Cg \times fg \quad (1)$$

$$fm + fg = 1 \quad (2)$$

where: $Cd$ is the $^{137}$Cs content of the deposited sediment (Bq kg$^{-1}$); $Cm$ is the $^{137}$Cs content of the sediment derived from the inter-gully area (Bq kg$^{-1}$); $Cg$ is the $^{137}$Cs content of sediment derived from the gully areas (Bq kg$^{-1}$); $fm$ is the relative sediment contribution from the inter-gully area (%); and $fg$ is the relative contribution from the gully areas (%).

The average $^{137}$Cs content of sediment mobilized from the inter-gully area and from the gully area were 3.9 Bq kg$^{-1}$ and 0.02 Bq kg$^{-1}$, respectively, in 1993. Allowing for radioactive decay the corresponding values for 2001 were 3.24 Bq kg$^{-1}$, and 0.017 Bq kg$^{-1}$, respectively. Using these values for the $^{137}$Cs content of sediment delivered from the inter-gully and gully areas, the relative contributions from the two sources during the years 1994–1996 were estimated using Equation (1). Values of 23%, 15% and 6% were obtained for the inter-gully area, whereas the equivalent values for the gully areas were 77%, 85% and 94%, respectively. The associated estimates of specific sediment yield from the inter-gully and gully areas for the years 1994–1996 are listed in Table 2.

During the period 1973–1977, annual precipitation totals ranged from 353.6 mm in 1974 to 670.3 mm in 1977, and the magnitude of the annual sediment yield was closely related to the annual precipitation. However, the relative contributions from the inter-gully and gully areas remained fairly constant and ranged between 17.0% and 24.2% for the inter-gully area and 75.8% and 83.0 % from the gully area. The annual sediment yields during the period1994–1996 were significantly greater than those during the period from 1973 to 1977.

**Table 2** A comparison of sediment yields before and after cessation of cultivation in the Zhaojia Gully Catchment.

| Year | Annual precipitation (mm) | Flood events | Specific sediment yield of the catchment (t km$^{-2}$ year$^{-1}$) | Mean $^{137}$Cs content of deposits (Bq kg$^{-1}$) | Relative sediment contribution % | | Specific sediment yield (t km$^{-2}$ year$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Rolling plateau | Gully | Rolling plateau | Gully |
| 1973 | 553.2 | 2 | 9153 | 1.40 | 19.5 | 80.5 | 4093 | 14859 |
| 1974 | 353.6 | 3 | 9955 | 1.14 | 17.0 | 83.0 | 3625 | 17093 |
| 1975 | 513.0 | 3 | 7424 | 1.50 | 23.2 | 76.8 | 3572 | 11768 |
| 1976 | 518.7 | 4 | 22455 | 1.12 | 17.2 | 82.8 | 8008 | 38747 |
| 1977 | 670.3 | 3 | 32472 | 1.55 | 24.2 | 75.8 | 16113 | 50919 |
| 1993 | 429.8 | 2 | 4627 | 0.75 | 23 | 77 | 2008 | 7580 |
| 1994 | 536.9 | 3 | 33034 | 0.75 | 23 | 77 | 14335 | 54119 |
| 1995 | 508.1 | 4 | 24851 | 0.49 | 15 | 85 | 7034 | 44944 |
| 1996 | 540.3 | 5 | 31068 | 0.18 | 6 | 94 | 3517 | 62136 |

The specific sediment yields of 1994 and 1996 were 33 034 t km$^{-2}$ year$^{-1}$ and 31 068 t km$^{-2}$ year$^{-1}$, respectively. These values are close to the specific sediment yield of 32 472 t km$^{-2}$ year$^{-1}$ for 1977, but the annual precipitation totals for 1994 (536.9 mm) and 1996 (540.3 mm) were considerably less than the value of 670.3 mm recorded in 1977 (Fig. 3). The relative sediment contribution from the inter-gully area has also sharply decreased from 23% in 1994, to 15% in 1995 and 6% in 1996, while that from the gully area increased from 77% in 1994, to 85% in 1995 and 94% in 1996.

Cessation of cultivation of the sloping land in the Zhaojia Gully has been shown to have resulted in an increase in the total sediment yield from the catchment, a decrease in the specific sediment yield and relative contribution from the inter-gully area, and an increase in

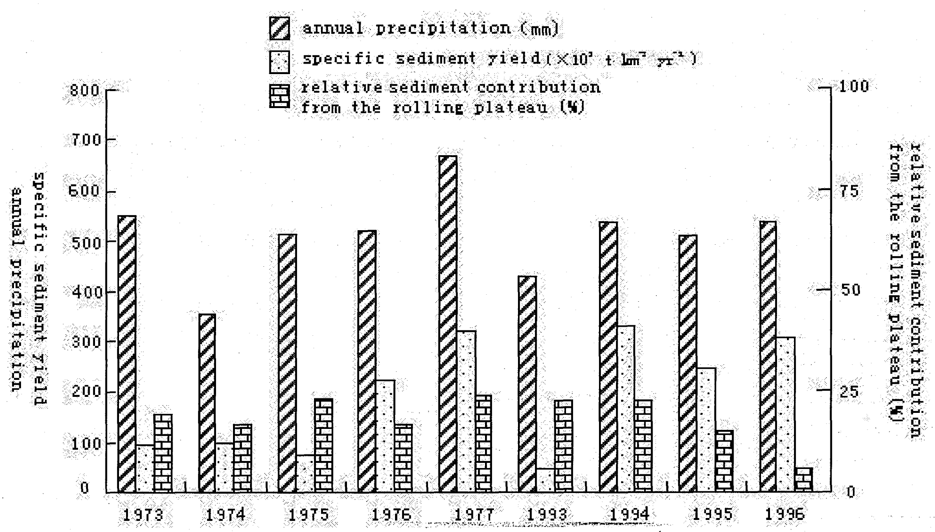


**Fig. 3** A comparison of annual precipitation totals, specific sediment yields, and the relative sediment contribution from the inter-gully area before and after the cessation of cultivation in the Zhaojia Gully catchment.

the specific sediment yield and relative sediment contribution from the gully area. It is suggested that compaction of the formerly ploughed soils resulted in an increased resistance to erosion, but decreased infiltration. Thus, although rates of soil loss from the inter-gully areas decreased, runoff amounts increased. An increase of runoff input to the gully areas could be expected to result in an increase in erosional activity and mass movements, causing an increase in the specific sediment yield and relative contribution from the gully areas and in the total sediment yield from the catchment

Loess landscapes are very sensitive to changes in the runoff regime. Changes in the runoff regime caused by cessation of cultivation in the inter-gully area can be expected to result in increased erosion until the terrain adjusts to the new runoff regime. This adjustment may take an extended period and soil erosion is likely to become more severe in the gully area. However, rates of erosion within the gully area and the sediment yield from the catchment can be expected to reduce in the longer-term as the vegetation cover in the catchment fully recovers.

## CONCLUSION

The mean specific sediment yield of 29 650 t $km^{-2}$ $year^{-1}$ for the period 1994–1996 after the cessation of cultivation is 2.2 times the long-term mean annual specific sediment yield of 13 413 t $km^{-2}$ $year^{-1}$ from the Zhaojia Gully catchment. This increase in sediment yield associated with cessation of cultivation was coupled with a decrease in both the absolute and relative contribution from the rolling plateau area and an increased absolute and relative contribution from the gully area. It is suggested that compaction of the formerly ploughed soils resulted in increased erosion resistance, but decreased infiltration, so that erosion rates decreased but runoff amounts increased within the inter-gully area. The increased runoff entering the gully area caused an increase in erosional activity and mass movements, resulting in an increased sediment yield and relative sediment contribution from this area of the catchment, as well as an increase in the specific sediment yield from the overall catchment.

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