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The effects of forest in controlling gully erosion

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Abstract On the loess plateau of the Yellow River basin, the landscape is intensively dissected by steep gullies. The loss of soil and water caused by gully erosion is serious. The gullies, although unfavourable for agricultural development, are good places for planting trees and grasses. Trees and grasses grow several times faster in the gullies than on the relatively dry ridge summits and slopes, and give better economic yields. The loss of soil and water from the gully systems is very high, the sediment concentrations of flood water can be very high, and scouring may be a serious problem. In view of their capability to reduce flow velocities and volumes and flood peaks and their soil binding properties, trees and grasses have proved very effective in reducing sediment loads. The manmade forests established in Yangjiagou, with forest cover of 40% mainly growing in the gullies, have reduced sediment yields by as much as 92.5%, even during storms. Through site investigations and analyses, we suggest planting fast growing trees at a high density linked with comprehensive improvement. In this way, we can effectively control soil erosion and produce greater economic benefit.

INTRODUCTION

The portion of the Yellow River basin extending from Longyangxia in Qinghai Province to Taohuayu in Henan Province covers an area of 60×10^4 km^2, or 80% of the total river basin. It coincides with the loess plateau characterized by a covering of deep loess and ranges of undulating hills, cut by dense networks of gullies. The soils are highly porous, the vegetation is scarce, and soil erosion is very serious. The area represents the main sediment source of the Yellow River, the most sediment-laden river in the world. In the past the cause of the high sediment loads was neglected for a long time and attention focussed on river training and levee works along the lower reaches of the river. With an increasing population and agricultural production, soil erosion is becoming more and more serious. The annual soil loss has reached 16×10^8 t in modern times. As a result of such soil erosion, the productivity of the land in the middle reaches of the river is declining, the river channels in the lower reaches are silting up and floods are becoming more frequent – all problems for the people who live in this region. Since the 1930s, and especially since the 1950s, more attention has been directed to researching this problem and to designing control measures. Based on the practices of the past 40 years, and through both observation and analysis, we present our assessment of the use of forests to control gully erosion in order to seek more effective control methods and measures.

THE BENEFITS OF FOREST PLANTING IN GULLIES FOR REDUCING SEDIMENT YIELDS AND FLOOD DISCHARGES

Morphologically, the loess plateau is composed of plateaux (flat plateau land), slopes and gullies (Fig. 1). A surviving area of natural forest in the hilly gullied region of Ziwuling on the boundary of northern Shaanxi and eastern Gansu, and the small Nanxiaohegou drainage basin on the gullied loess plateau of eastern Gansu are taken as examples for discussion.

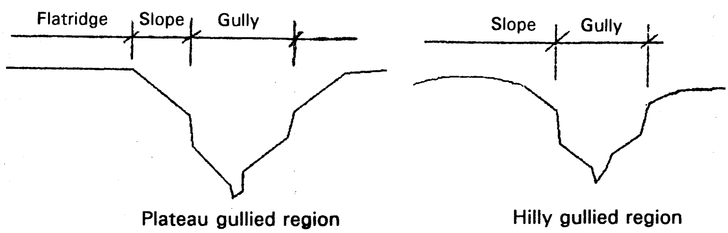

Fig. 1 A schematic section of the typical landforms of the loess plateau.

Ziwuling is an area of natural forest which has developed after local people left their homes in the war 120 years ago. The distribution of trees in this district is such that the tree cover in the gullies is better and denser than that on the flat ridges and the slopes. The forest on the flat ridges and slopes has been subject to destruction in modern times, because the flat ridges and slopes are relatively flat and often cultivated, whilst in the gullies, which are less suitable for cultivation, the higher water content provides better conditions for forest growth, and the forest often survives for a long time.

This pattern of forest distribution can further explain the problem being discussed. Because the area of gullies generally accounts for 30-50% of the total basin, whereas the forest area commonly comprises about 40% of the basin, most of the trees are concentrated in gullies for sediment reduction when the proportion of forest is less than 40%.

In the Shigiao basin (Fig. 2) where the forest has remained and accounts for 45% of the total basin area, and most of the flat ridges and slopes are cultivated, the sediment yield has been reduced by 95% mainly due to the forest remaining in the gullies. There are two small sub-basins in the Nanxiaohegou basin (30.6 km^2): namely, Yangjiagou (0.87 km^2) and Dongzhuanggou (1.15 km^2). They are located in close proximity with similar

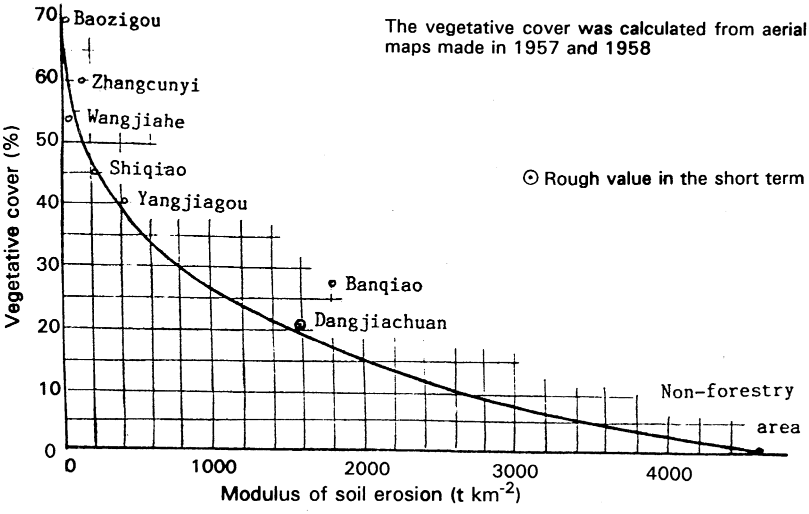

Fig. 2 Relationship between the ratio of forest area to the total basin area and specific sediment yield.

natural and social-economic conditions. In the Yangjiagou basin the planted forest area comprises about 40% of the total basin, while in the Dongzhuanggou basin no erosion control measures have been implemented. A comparison of runoff and sediment yield from the two basins enables the degree of reduction caused by the forest cover in the Yangjiagou basin to be calculated (cf. Table 1).

The reduction in flood runoff and sediment yield documented for the Yangjiagou basin can be attributed to the planting of forest in the gullies for the following reasons:

(a) 80% of trees in the Yangjiagou basin are concentrated in the gullies, and

Table 1 Annual reduction of flood runoff and sediment yield in the Yangjiagou basin.

Year	Annual reduction of flood volume (m^3 km^{-2}) (%)	Annual reduction of sediment yield (t km^{-2}) (%)
1954	27.2	58.8
1955	64.3	80.2
1956	50.3	71.9
1957	29.6	31.0
1958	47.9	97.7
1959	85.7	99.4
1960	51.9	85.7
1961	25.9	84.1
1962	49.9	99.5
1963	47.4	97.4
1964	29.3	94.1
1965	-9.8	98.1
1976	73.7	91.1
1977	69.7	77.6
Mean for 1958-1977	47.2	92.5
Total mean	45.9	83.3

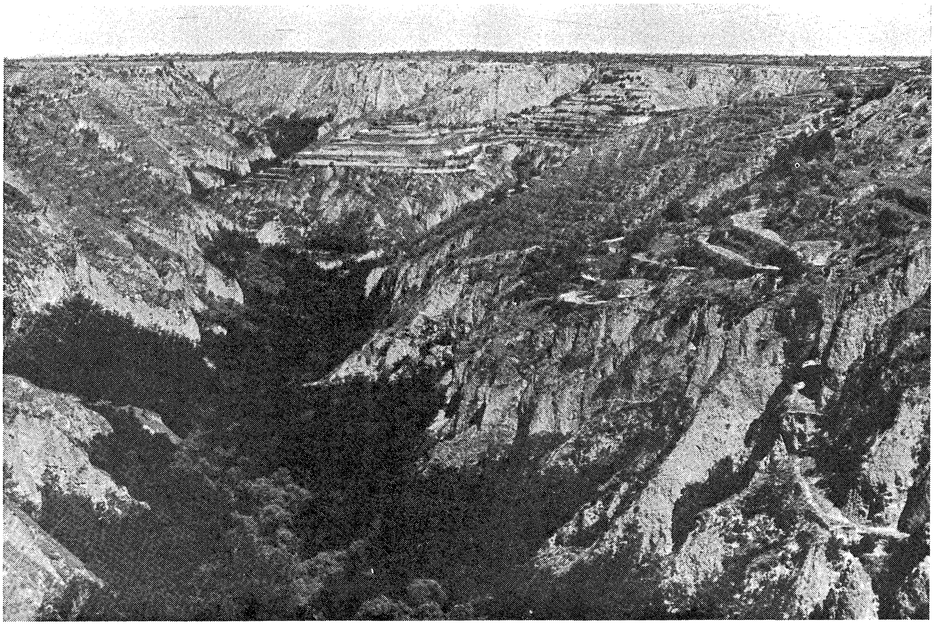

Fig. 3 Trees in the Yangjiagou basin are concentrated mainly in the gullies (photo taken August 1980).

the trees grow densely and lushly, along with grasses. The growth rate of the forest in the Yangjiagou basin during the 1950s/1960s, according to measurements made by forest researchers, was 22 times that of the trees growing on the flat ridges. This comparison was of fast-growing trees such as scholartree in the gullies with apricot trees on the flat ridges. On the flat ridges and slopes, the trees and grasses grow slowly, with a low survival rate because of drought, and give rise to a sparse forest cover of "small old trees", which afford only a limited effect in sediment reduction (see Fig. 3).

(b) Runoff and sediment yield from the flat ridges and slopes which have no control measures, account for 19.1% and 3.2% of the respective totals. The flat ridges and slopes are not the main sources of runoff and sediment in the Yangjiagou basin.

(c) In the Shiqiao basin the grassland vegetation remaining on the flat ridges and slopes after the trees had been destroyed is better than that in the Yangjiagou basin, and is one of the factors accounting for the low sediment yield. In the Yangjiagou basin this factor is not significant, because both basins exhibit similar degrees of sediment reduction in Fig. 2. This emphasises the important role of the forests in the gullies, after the forest on the flat ridges and the slopes has been destroyed. The Shigiao watershed shows no difference in sediment reduction since the sediment yield from the cleared areas is still many times higher than that from the areas of surviving forest or planted forest. That is why the

Bangiao basin plots above the curve in Fig. 2 and this also indicates that the effect of forest in the gullies is greater than that in other parts.

THE RAPID EFFECT OF FOREST IN CONTROLLING GULLY EROSION

Scholartrees, poplars, willows and *Hippophae rhamnoides* were planted in the Yangjiagou basin in 1954-1955, in association with tree-pits and check dams. The sediment reduction was 58.8% in 1954, 80.2% in 1955, 71.9% in 1956 and 31.0% in 1957. During this period the trees had not grown significantly, and the effect was mainly due to the engineering measures. The reduction was lower in 1957, because the capacity of the engineering measures was exceeded and some were destroyed or damaged by a storm in that year, and they have not been repaired since. Since 1958, however, the reduction has been maintained at around 90%. This demonstrates that the effects of the tree planting are both rapid and stable (see Table 1).

On the contrary, in the Nanxiaohegou basin, where the control works were initiated in 1952, and emphasis was placed on the flat ridges and slopes, with a major labour input, but without planting of trees in the gullies, the sediment reduction was 47.7% in 1954-1960, 45.8% in 1961-1976 and 49.9% in 1977-1990, and remained almost unchanged over this period. The control measures introduced on the flat ridges and the slopes are less effective in sediment reduction. Moreover, the sediment reduction mentioned above also included the effect of three dams (about 20%). The control measures on the flat ridges and slopes themselves therefore only contributed a reduction of 26-30%.

THE IMPACT OF EXTREME EVENTS ON SEDIMENT YIELD REDUCTION

Comparing the specific sediment yields from the Yangjiagou and Dongzhuanggou basins for events with maximum flood peaks and flood volumes, it is clear that the reductions achieved in ordinary years are maintained in years with big floods. The effect of the natural forest and plantations is almost the same.

On 2 August 1980, a rainstorm of 70.4 mm occurred in the Yangjiagou basin, and caused a flood with a frequency of once in five years. On-site investigations showed that the flat ridges were essentially without soil conservation measures, and that large amounts of runoff were generated from the flat ridges. The density of trees in the gullies was reduced to 50% of that in the 1960s-1970s, but the effect on sediment reduction was still maintained at 71.4%.

On 23 July 1988, a rare rainstorm of 44.7-135.1 mm in 2.5 h was recorded over the Yangjiagou basin. This corresponded to a rainfall frequency of once in 200 years if the average rainfall is taken as 89.8 mm for 2.5 h, or once in 1000 years if the average rainfall is taken as 135.1 mm. If a daily rainfall of 89.9 mm is used, this storm corresponds to a frequency of once in 75 years. The flood peak discharge and the flood volume were the largest recorded in the Yangjiagou basin for 34 years. Although undercutting and scouring of the gully bed occurred (this is connected to the reduction of the tree cover in the past 10 years) the amount of erosion of the gully bed was just 8% of that in Dongzhuanggou. This shows that the effect of tree planting in the gullies is maintained even when high magnitude rainstorms occur.

THE MECHANICS OF REDUCED SEDIMENT YIELDS FROM FORESTED GULLIES

Soil loss from a basin is caused by raindrop impact and splash, the kinetic energy of slope runoff and scouring by runoff along rills and gully beds. The erosion by the kinetic energy of slope runoff is greater than the erosion by raindrop impact, and gully erosion in the form of undercutting and scouring is greater than the sheet erosion on the slopes. According to analysis undertaken for the Nanxiaohegou basin, the annual mean sediment concentration of runoff is 88.2 kg m^{-3} on slopes, 20 kg m^{-3} on flat ridge farmland and 81.2 kg m^{-3} averaged for cultivated and uncultivated lands on flat ridges and slopes, while the sediment concentration of the flow in gully channels is 500-700 kg m^{-3}.

Sediment production from the gully accounted for 86.3% of the total for the watershed, most of which is produced by undercutting, landslides, collapse flows and mud flows of the red soil cliffs of the gullies. This feature of erosion is characteristic of the gullied regions of the Middle Yellow River, where gully erosion is becoming increasingly serious until the bed rock is exposed.

The sediment content of flood water in channels in the middle reaches region is normally in the range 500-1000 kg m^{-3} and the maximum is over 1500 kg m^{-3}. Recent research on hyper sediment laden flow shows that sediment transport often takes the form of hyper sediment laden flow in small- and medium-sized basins. Hyper sediment laden flow is a form of mud flow, where the silt normally does not settle, turbulence is low and the energy loss is less, so the sediment is easily transported. Because the specific weight of the sediment-laden flow is high and close to the saturated bulk weight of the river-bed material, the bed material is readily scoured by the flow and the flow is highly erosive. If we draw a curve for measured data from the Nanxiaohegou basin and combine it with the experimental data of Qian Ning *et al.* (1979) we can investigate the relationship further. The results indicate that when the sediment content is above 200 kg m^{-3} and increases, the hydraulic parameters required for transport tend to decrease.

The analysis shows that when the sediment content increases, the flow can both transport the sediment and also scour the channel. The erosion produced by hyper sediment-laden flow makes the channel bed narrower and deeper, and the narrow-deep channel in turn is more favourable for movement of hyper sediment laden flow. Such a process is self perpetuating, since there is abundant sediment supply from landslides, bank collapses and mud flows. It is for this reason that the sediment yields from gullies are much higher. Shallow-broad channels are unfavourable to the hyper sediment laden flow and provide good condition for siltation. Therefore densely planted trees in the bottom of gullies are capable of binding the soil and damping the hyper sediment laden flow and consequently of reducing sediment loads.

Three year old *Hippophae rhamnoides* growing in the Yangjiagou basin had a total root length of 7 m in a 0.5 m deep soil layer. Seven year old *Hippophae rhamnoides* had a total root length of 26 m. Dense root systems bind the soil and increase erosion resistance. The trees have an impact on flow conditions. Dense forests in the gullies and especially in the gully bottoms has promoted the deposition of 0.5 m of sediment on the gully bed over the 10 years since 1958. In the natural forest region of Wangjiahe, due to the effects of forests, the gully bed had been raised by siltation more than 5 m over the past 120 years. On the contrary, as forests had been destroyed, in the Dangjiachuan basin and the neighbouring Wangjiahe basin, the gully beds have cut down over 5 m in 30 years. The establishment of the gully woodland enables the improvement of the gullies to extend gradually upwards, and as a result serious erosion such as landslides, collapses and mud flows have been controlled, because the resulting sediment has been retained and stabilized by the dense forest and grass.

One of the main reasons for the reduction in sediment yields is that the trees reduce the runoff. For example in the Dongzhuanggou study there is a good correlation between sediment discharge (Q_s) and the flow discharge (Q): $Q_s = 550\ Q^{1.28}$. Table 1 shows the effects of forest in reduction of flood peaks and flood volumes as well as sediment yields. Assuming an annual reduction of flood volume by 45.6%, the corresponding reduction in sediment yield would be 54%.

To sum up, in the gullied loess areas and especially in the secondary and small gullies, where the bed is composed of unconsolidated loess, sediment yields from the gullies are very high. Under these conditions, forests are very effective in reducing sediment yields. The main mechanism associated with the forests in sediment yield reduction is that the forest reduces flood magnitude and produces conditions unfavourable for hyper sediment laden flow.

THE ECONOMIC BENEFIT OF THE GULLY WOODLANDS

Increase of incomes

Table 2 shows the total income from the Yangjiagou basin. From Table 2 we

Table 2 Total income from 1954 to 1977 for the Yangjiagou basin.

Item	Agriculture (t)	Grass below trees (t)	Firewood (t)	Seed of trees	Timber (pieces)	Manmade grassland (t)	Timber savings (m^3)	Total amount
Amount	156	350	400	-	6000	215	4000	-
Output value (10^4 yuan)	5.32	0.7	1.60	7.86	1.20	1.80	32.00	49.75

can see that the total income has increased seven times compared with that before treatment, mainly due to the forestry.

Benefits for animal husbandry

The conflict between forestry and animal husbandry is a major problem in many areas of the middle reaches of the Yellow River. If we increase the management of trees and adopt measures, including the plugging of gullies to grow grass and mowing the grass at regular intervals etc., both forestry and animal husbandry can benefit. In the Yangjiagou basin there was overgrazing before the management was introduced. The vegetation had no chance to recover, and grass was lacking for four months of the year. 120 sheep were reared, but the death rate of the sheep in springtime was 33%. After planting trees and intensive management, the uncultivated land has been used for forestry, the output of grass has doubled, the number of sheep has increased to 150, but the death rate in spring has dropped to 17.8%.

DISCUSSION

The afforestation of gullies is not in conflict with agriculture. It is able to both significantly reduce sediment yields and increase the economic income, and it is less labour intensive. For example, in the Yangjiagou basin, the afforestation was completed in 1945-1955, and the forest was maintained in the following years as fuel and wood forests. If other measures had been adopted, the volume of work would have been much greater, and more time and more labour would have been needed. When comprehensive control of soil erosion is implemented we should introduce densely planted fast-growing trees in the gullies along with contour trenching or ditching. The afforestation should begin first in the small lateral gullies and gradually expand to the lateral gullies and eventually to the main gullies (in the initial stages the trees should be planted away from the flood channels). In this way, that is not in the sequence flat ridge → slope → gully, we may succeed in significantly reducing the sediment influx into the Yellow River by first afforesting the gullies.

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REFERENCE

Qian Ning, Wan Zhaohui & Qian Yiying (1979) About the problem of the hyper sediment laden flow of the Yellow River (in Chinese).