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# Anthropogenic influences on changes in the sediment load of the Yellow River, China, during the Holocene

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**Abstract** Using data on formation of the Loess Plateau of central China, loess — palaeosol sequences, pollen analysis, historical geography, and long — term experimentation on rates of soil erosion, it is demonstrated that current serious erosion on the Loess Plateau is mainly due to human destruction of the natural vegetation and irrational land use. These two modifications greatly reduce soil — infiltration capacity and resistance of the soil to erosion. The increase of soil erosion began ca. 5000 BP at which time a hunting and pastoral life began to change gradually to a sedentary life centred around cultivation. Using the volume of Holocene loessic sediments on the continental shelf of the Bohai, Yellow, and East China Seas, it is estimated that the present sediment load of the lower Yellow River is at least three times greater than it was during the Holocene. Although human—induced soil erosion in the Loess Plateau began earlier, it was not until the Tang dynasty (about 1000 BP) that it began to increase rapidly. According to available information on projected and planned economic development and major conservancy works in the Yellow River basin over the next 25 years, it is predicted that sediment load of the lower Yellow River will be reduced by about 30%～40% in the early twenty—first century.

**Key words** Sediment load Yellow River Loess Plateau soil erosion land use anthropogenic effects rainfall simulation experiments China

## Introduction

The Yellow River discharges to the sea about $1\times10^9$ tons of fluvial sediment per year (as measured at Lijin, about 100km inland) and accounts for approximately 7% of the total annual input of fluvial sediment to the oceans from all the world's major rivers (Milliman, 1989). Thus, changes in the sediment load of the Yellow River over the last 10 000 years is of great significance to the sediment budget of the world's oceans.

It has been estimated that nearly 90% of the sediment of the Yellow River comes form the Loess Plateau (Figure 1; Ren et al. ,1986). The remarkable loess—palaeosol sequence of the Loess Plateau has been studied in great detail in recent years. Together with an historical record going back some 5000 years and many rich archaeological findings, these data provide Chinese geoscientists with an unparalleled opportunity to study Holocene changes in the sediment load of the Yellow River.

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## The nature of loess

Loess is mainly a wind—borne sediment blown from the deserts of northwest China (Liu et al., 1985). It is generally assumed that loess, by its nature, is highly erodible. However, detailed studies of the microtexture of loess and wind—borne dust have shown that they are composed of three kinds of particles, each type having its own particular shape. During accumulation, differently shaped dust particles are packed together, leaving many interstitial voids. In its pristine state, therefore, loess is quite porous.

Recent pollen analysis has demonstrated that during periods of loess accumulation, the natural vegetation consists of steppe or dry steppe. With the help of grass and grass roots, the porosity of loess is enhanced. Where the natural vegetation is intact, loess possesses both a high permeability and a high water—storage capacity so that no surface runoff is generated even during a rainfall of 500 — 1000mm with rainfall intensities of 2 mm per minute. Therefore, loess is locally known as a water reservoir in the soil'. Thus, it is only with the human destruction of natural vegetation that serious soil erosion is initiated (Zhu and Ren, 1992).

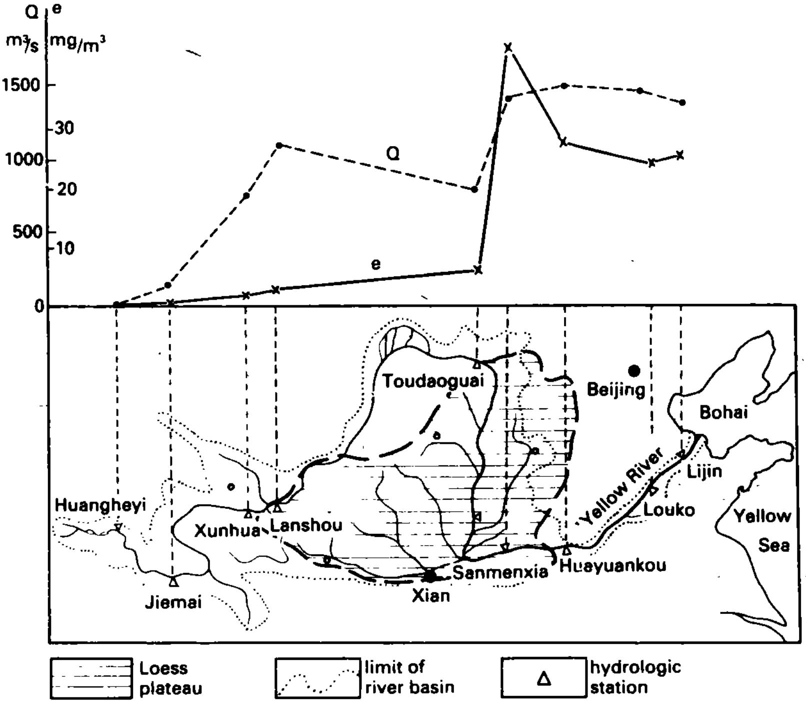



Figure 1 Water discharge (Q) and sediment concentration (e) at selected stations on the Yellow River (30—year average, 1950～1979). Note the abrupt increase in sediment concentration as the river flows through the Loess Plateau (modified after Ren and Shi, 1986).

## Natural vegetation of the Loess Plateau during the last 130 ka

Recent pollen research on the loess above the $S_1$ (last interglacial) soil in the Luochuan profile in Shaanxi Province[1] has shown that the natural vegetation of the Loess Plateau during the last 130 ka was essentially steppic in type: dry steppe in the glacials, steppe with scattered trees in the interglacials and wooded steppe during the Holocene 'Climatic Optimum'. Generally speaking, the Holocene was a warm period (i. e., of interglacial type), vegetation being broadly similar to that in the Pleistocene warm periods when the many buried palaeosols were formed, i. e., steppe in the western Loess Plateau, wooded steppe in northern Shaanxi and wooded steppe with abundant trees in the Wei—he basin (Liu, 1990). In the Holocene loess, three or four palaeosol layers have been found. This, together with other evidence, indicates that climatic fluctuations characterized the Holocene. On the whole, however, the Holocene has essentially been a warm and humid period, with plentiful precipitation and a well — developed natural vegetation cover (largelv a wooded steppe) on the Loess Plateau (An et al. ,1991;Zhou et al. ,1991).

According to written historical records, archaeological findings and pollen data, it has been demonstrated that in the period 4000～3000 BP, vegetation on the Loess Plateau consisted of shrub and steppe with a considerable area under a forest cover (Zhu,1982;Shi et al. ,1985;Liu,1988; Wang,1990).

'Shen Nong' is widely acknowledged as the forefather of farming in China. Actually, 'Shen Nong' is the name of a tribe living in the Baoji area of the Wei—he basin in Shaanxi Province. It is this tribe which brought about important changes in the life style of the Chinese people with the change from hunting and gathering to primitive farming. This change happened between about 7000 and 5000 BP (Liu, 1990; Meng, 1990, 1991). On the Loess Plateau, there were rich grasslands and many trees in prehistoric times to support the hunting and gathering economy. Even as late as ca. 2400 BP, when iron implements had yet to become widely used, grazing (chiefly pastoral) was still the major type of land use in this region.

On the Loess Plateau, type of land use has a distinct effect upon soil erosion and consequently also on sediment concentration in the rivers. It is well—known that the name of the Yellow River derives from its heavy sediment load. In earlyhistorical times, the Yellow River was generally known as 'Da He' or 'Great River'. It is only since the seventh century AD (the Tang dynasty) that the name 'Yellow River' has been widely used in historical documents. This indicates that before the seventh century, the Yellow River was not very muddy and its sediment concentration was not as high as at present[2]. The same is true for many major tributaries of the Yellow River which derive their sediment from the Loess Plateau. For example, according to a poem of about 3000 BP the Jing He was a clean river ('the river water so clean that its bottom could be seen'). However, because of extensive cultivation, the river water turned very 'muddy' by about 2300 BP. The Yan He is currently a very muddy river, but it was called 'Clean River' in about 2000 BP. Such name changes indicate that the high sediment concentrations of the Yellow River and its tributaries in the last thousand years or so were mainly the result of excessive cultivation of the Loess Plateau.

## Factors affecting soil erosion on the Loess Plateau and the effects of human activity

Major factors affecting soil erosion on the Loess Plateau include the nature of loess, ground slope, rainfall intensity, rainfall type, vegetation cover and soil conservation measures. Of these six factors, rainfall intensity and rainfalll type are purely natural, soil — conservation measures are anthropogenic, while the nature of loess, surface gradient and vegetation cover, although basically natural factors, have been greatly altered from their original 'natural' conditions by human activity through time.

In terms of the effect on soil erosion, vegetation is the most important factor. Under an unmodified vegetation cover of grasses, the loess proves quite resistant to erosion. After destruction of the natural vegetation, however, it becomes readily erodible, as shown by experimental results obtained by the Northwest Institute of Water and Soil Conservation of the Chinese Academy of Sciences (Table 1).

Table 1 Amount of soil eroded under different vegetation (kg/$hm^2$)

| Vegetation | Ziwu Ling[1] | Ansai[2] |
| --- | --- | --- |
| Forest | 60 | 375. 2 |
| Grassland | 90 | 1468. 9 |
| Crops | 3720 | 44171. 8 |

[1]Ziwu Ling, border between Shaanxi and Ningxia, data for June—September 1963.

[2]Ansai, middle Shaanxi, annual amount, five—year average value, slope 22°～28°.

Recent experiments on a slope of 20° with a simulated rainfall duration of 30 minutes (undertaken by the Institute of Water and Soil Conservation at Ziwu Ling) yielded the results set out in Table 2. These experiments clearly demonstrate that, with increased rainfall, soil erosion of farmland is greatly accelerated, but that the same level of rainfall increase has practically no effect on forested land. Similar simulated rainfall experiments on terrain covered by shrub and grass at Renjiatai, Fu Xian (northern Shaanxi Province), on a slope of 8° clearly show that soil erosion rates are lower than is the case on bare, cultivated land at lower rainfall intensities (Table 3).

Table 2 Soil erosion by artificial rainfall at Ziwu Ling

| Rainfall intensity (mm per minute) | 1. 26 | 1. 26 | 1. 91 | 1. 91 | 2. 37 | 2. 37 |
| --- | --- | --- | --- | --- | --- | --- |
| Land use | forest | farmland | forest | farmland | forest | farmland |
| Soil eroded (kg) | 0 | 3. 05 | 0 | 16. 83 | 0. 05 | 37. 46 |

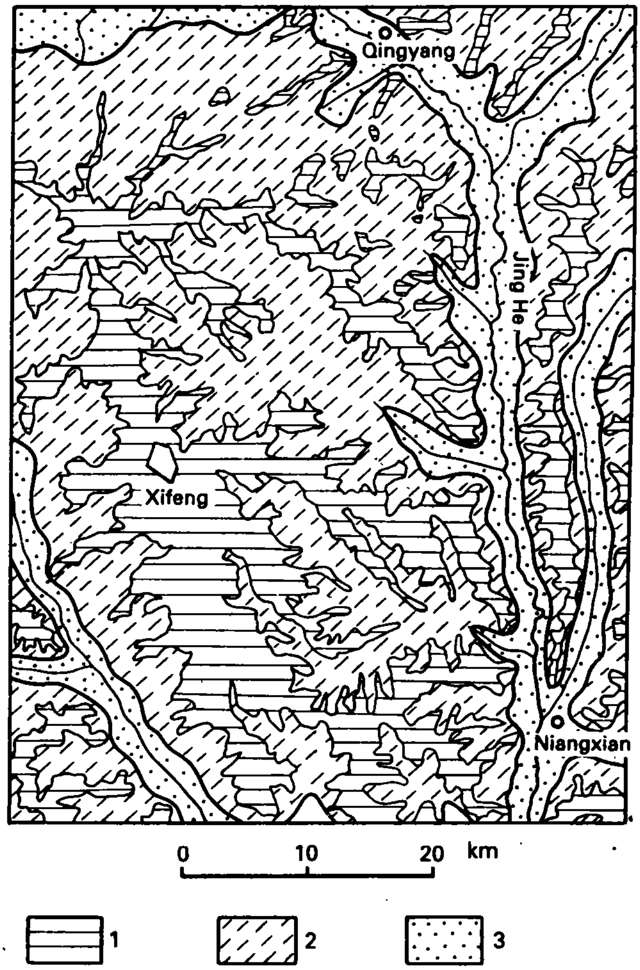
Table 3 Soil erosion by artificial rainfall at Renjiatai, Fuxian, Shaanxi Province

| Land—use type | Vegetation cover(%) | Rainfall intensity(mm per minute) | Soil eroded(bareland=100) |
| --- | --- | --- | --- |
| Shrub | 85 | 3. 46 | 10 |
| Grass(slope 15°) | 80 | 3. 05 | 20 |
| Bare,cultivated land | 0 | 1. 92 | 100 |

Recent experiments by Dr Tang Keli on grassland at Ziwu Ling using artificial rainfall yielded similar results[3]: experimental plot 1. 5m × 5m, slope 18°～20°, total rainfall 48. 4mm, rainfall intensity 1. 56mm per minute, natural grassland (grass cover 98%～100%), soil eroded 0; grassland, cultivated, soil eroded 3 524. 1g. Vegetation reduces soil erosion because any increase in plant roots greatly increases soil permeability and resistance to scouring in the Loess Plateau. Recent experiments demonstrate that with each increment of grass—root density of 100 per $100cm^2$, under a rainfall intensity of 2.0mm per minute and a rainfall duration of 30 and 120 minutes, the amount of rainfall entering the soil is increased by 16.98 and 63.36mm, respectively (Li et al., 1992).

The experimental results clearly indicate that, under forest or grass cover, rainfall intensity and slope have little effect on soil erosion and that it is only after human destruction of vegetation that rainfall and slope become important factors in soil erosion. It may be tentatively concluded from this that, during the Holocene (especially before 2500 BP when the natural vegetation on the Loess Plateau remained essentially intact) rainfall variations had little effect on soil — erosion rates and, consequently the sediment load of the Yellow River was much less than it is at present.

Slope gradient also has a clear effect on soil erosion. According to an experiment at Ansai by the Northwest Institute of Water and Soil Conservation (39 measurements in five years), using rainfall intensities of 0.25 ~ 0.50mm per minute for 30 minutes ($I_{30}$ = 0.25 ~ 0.50mm per minute), the amount of eroded soil on a 28° slope was 5.9 times that on a 5° slope. Using a greater rainfall intensity ($I_30$ > 0.75), soil erosion was more than 10 times that seen on the 5° slope.




1. remnants of former plateau surface
1+2, plateau surtace in the Tang dynasty(618—907)
3. gullies and valleys

Figure 2 Erosion of a loess plateau surface in eastern Gansu Province, China, since the Tang dynasty (AD618—907)

It may be noted that, in prehistoric times, the relative relief of the Loess Plateau was not so marked as at present. Later, owing to the destruction of the natural vegetation, the widespread gentle and flat ground of the Loess Plateau was severely dissected into an intricate mosaic of innumerable deep gullies and steep hills. Between the seventh and tenth centuries AD (Tang dynasty), there were still many extensive flat plateau ('Yuan') in the Loess Plateau region. For example, Dongzhi Yuan in eastern Gansu was 42.5km long and 32km wide in the Tang dynasty but its width is now only 18 km at its widest part and only 0.5 km at its narrowest, its area having been reduced from 1051 $km^2$ in the seventh century to 412 $km^2$ at present. Thus, in Dongzhi Yuan alone, 639 $km^2$ of flat plateau has been eroded into gullies and hills in the last 1 300 years. At the present time, gullies are being rapidly cut into the flat plateau surface and headward erosion of gullies is progressing at an astonishingly rapid rate. The heads of many gullies are retreating at a rate of 3m/a (Figure 2). In Guyuan County, Ningxia Province, they are retreating at 6.78m/a (average AD 1957～1979, according to a comparative study using aerial photographs). The famous Luochuan Yuan in Shaanxi was a single large yuan in the Tang dynasty but it is now dissected into six small pieces.

Around Jungar Qi, on the border between Inner Mongolia and Shaanxi (i.e., the northern most part of the Loess Plateau), destruction of the natural vegetation has resulted in an increase in the area of gullies of 0.4 $km^2$ between AD 1957 and 1988, according to aerial photographic studies of a 7.7 $km^2$ experimental plot (Figure 3, Jin et al., 1990). Thus, in this small plot, 0.18% of the total area of flat ground is being lost every year. This is entirely the result of human activity.

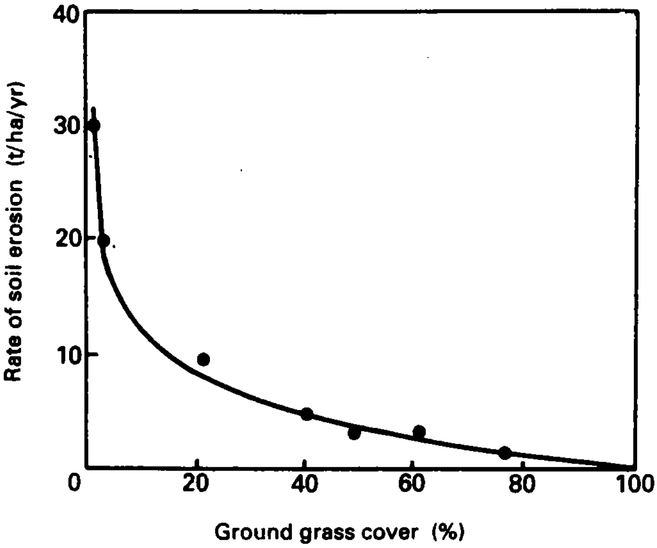


Figure 3 Rate of soil erosion in relation to ground grass cover in the northern border area of the Loess Plateau (after Jin et al., 1990)

From the above examples, it is evident that a great part of the present deep-gully and steep-hill landscape in the Loess Plateau is of anthropogenic origin dating only from the last 1 000～1 500 years. It is equally apparent that current serious soil erosion in the Loess Plateau is not a purely natural geological process and that the present huge sediment load of the Yellow River (1.6 billion tons per year at Shaanxian or Sanmenxia) is not a natural phenomenon that, as some Chinese geologists have suggested, existed since prehistoric times (Hong, 1990).

## Estimating the sediment load of the Yellow River in the Holocene

Although it is difficult to quantify the sediment load of the Yellow River in the Holocene, a best estimate can be obtained from a comprehensive study of records of the sediment loads of this river in the last 70 years, experimental data on the amount of soil erosion under different vegetation covers and land uses, data contained in the historical literature, pollen data in loess-palaeosol sequences and the volume of Holocene Yellow River sediment lying on the continental shelf.

Recent high — resolution seismic profiling on the continental shelf and clay — mineral analysis of Holocene shelf deposits have shown that the total volume of Holocene Yellow River sediment on the shelf is approximately 3 000 $km^3$ (Milliman et al. ,1987). It has been demonstrated that since about 1 000 BP, the Yellow River sediment discharging into the sea was similar to that observed in the last 70 years, i. e. , about 1 billion tons per year. Between about 2 500 and 1 000 BP, the boundaries between farming and grazing land — use types suffered frequent changes (Figure 4). For most of this period, however, the situation was one of approximately half farming and half grazing (Shi, 1985; Tan, 1987). In this period, there are many records of clear water in the Yellow River and its tributaries, although muddy water periods are also documented. However, the overall tendency in the change of water colour in these rivers is from clean to short — term muddy, then to long — term muddy until a time when no clear water was recorded. At the same time, the duration of clear Yellow River water changed from long to short term and the frequency of clear water shifted from high to low. All these changes indicate that more and more sediment was being carried down from the Loess Plateau to the Yellow River as soil erosion on the Loess Plateau became increasingly serious (Zhang, 1988). It seems reasonable to assume that the sediment discharge of the Yellow River reaching the sea between 2 500 and 1 000 BP was approximately half that of the average in the last 1 000 years, i. e. , about $5\times10^8$ tons per year, and that the total volume of sediment discharge in the last 2 500 years was 1 750 $km^3$. Assuming the normal span of the Holocene of 10 000 years, the sediment discharge of the Yellow River reaching the sea between 10 000 and 2 500 BP must have been about $1.7\times10^8$ tons per year.

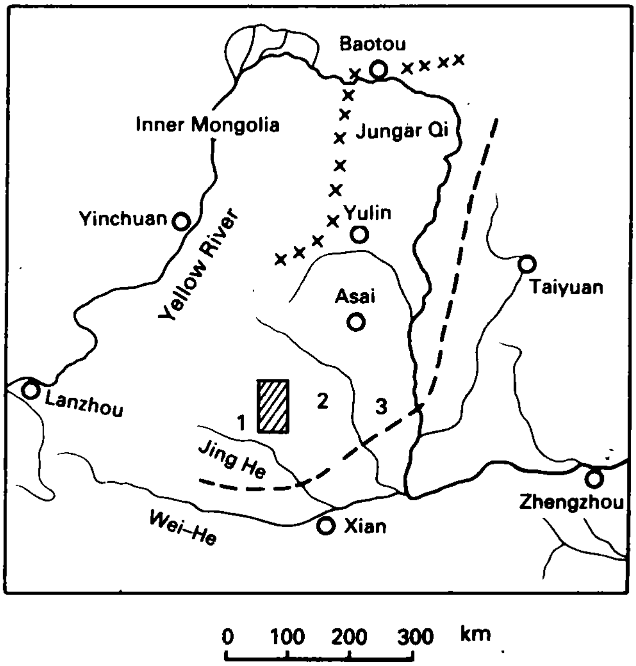



Figure 4 Changes of the boundary between farming and grazing (— — —) between the third century BC and (× × ×) the first century AD. Farming is to the south and east. 1—Dongziyuan; 2—ziwu Ling; 3—Lochuan

It may be noted that before 2 500 BP there were no dikes on the lower Yellow River. As a result, when the river debouched from the mountains at Mengjin (near Zhengzhou), it bifurcated into many distributaries and overflowed freely across the North China Plain so that a greater part of its sediment load was deposited on the plain and did not reach the sea. Sedimentation of the Hai — he and Luan — he in the early 1950s may be taken as a modern analogue because reservoirs had not been built on the upper and middle reaches of these rivers at that time and the channel of the Hai —

he had not been regulated and improved. Therefore, the Hai—he and the Luan—he deposited a large part of their sediment on the plain after leaving the mountains. At stations where the rivers debouch from the mountains, their total sediment load was $1.8\times10^8$ tons per year. It is estimated that about $1.2\times10^8$ tonsper year were deposited on the plain, leaving only $0.6\times10^8$ tons per yeay to reach the sea. Taking this as a reasonable approximation, it may be estimated that, between 2500 and 10 000 BP, the mean sediment load of the Yellow River at Mengjin was about $5\times10^8$ tons per year, or approximately one—third of the present value. Considering that a dry and cold Younger Dryas may have characterized the Loess Plateau during the early Holocene and that the area of deep gullies and steep slopes was increasing with the development of soil erosion, $5\times10^8$ tons per year may be a best estimate. However, in view of the strong dependence of soil—erosion rate on vegetation cover, the mean sediment load of the lower Yellow River before 2500 BP may have been much less than this estimate. Evidently, more research is needed.

It is interesting to note that there is a good, positive correlation between land use on the Loess Plateau and flood disasters along the Yellow River (Table 4). Although these flood disasters are governed by many factors, it is generally agreed that the predominant factor is the volume of the fluvial sediment load which, in turn, is highly dependent on vegetation and land use in the Loess Plateau; hence, the two correlate positively. From Table 4, rapid increases in the sediment load of the lower Yellow River as a result of human activity are therefore equally clear.

Table 4 Relation between land use in the Loess Plateau and the frequency of flood disasters along the lower Yellow River (Zhou,1984;Tan,1987;Zhang,1950)

| Period | Land use in the Loess Plateau | Frequency of flood disasters[1] |
|---|---|---|
| 1200—221 BC | Grazing, very little farming | 0.5 |
| 221 BC—AD 8 | Cultivation and settlement | 5.7 |
| AD 9—618 | Much farmland abandoned,returned to grazing | 1.3 |
| AD 618—907 | Mainly half farming | 10 |
| AD 960—1279 | Cultivation and destruction of vegetation | 50 |
| AD 1279—1911 | Continued | 200 |
| AD 1912—1936 | Continued | 400 |

[1] Number of flood events per century.

It should be noted that in the recent period (1000 BP to the present, when much of the natural vegetation cover was destroyed), the amount of precipitation has a significant effect on the short—term (10—year or even annual) variation in the sediment load of the Yellow River. For example, in the dry period 1920～1929, the average annual sediment load at Shaan Xian station was only $11.9\times10^8$ tons, in contrast to $17\times10^8$～$18\times10^8$ tons during the wet period 1930～1959. Because of the monsoonal nature of the climate, yearly variations in sediment load are much greater. At Shaan Xian, the lowest recorded annual sediment load is only $4.88\times10^8$ tons (1928), compared to the highest value of $39.1\times10^8$ tons (1933). However, these considerable short—term and annual variations have little effect on long—term averages of 40 years or longer. Thus, the overall average annual sediment load at Shaan Xian in the periods 1919～1959 and 1963～1979 was $15.7\times10^8$ and

16. $1\times10^8$ tons, respectively. It seems clear, therefore, that fluctuations of short−term dry and wet periods do not greatly affect our estimates of long−term changes in the sediment load of the Yellow River during the Holocene.

Substantial increases in the fluvial sediment load as a reault of human settlement and cultivation has also been documented in river basins in other parts of the world. For example, it has been estimated that the present sediment loads of the Atlantic−draining rivers of the United States are four to five times greater than before European settlement (Chorley et al. ,1984).

High sedimentation rates in part of Chesapeake Bay and the Appalachian Piedmont over the last century have also recently been documented and have been attributed to agricultural land clearance in the Appalachian uplands (Kearney and Stevenson,1991). However, the Yellow River of China, with very long historical records and high−resolution climatic and vegetation data in its loess−palaeosol sequence, provides an interesting and illuminating example of the changes on longer time scales.

## Future change

The prediction of climate change at regional−level precision is still subject to great uncertainty. Precipitation changes, which are most important in the present study, are particularly uncertain (Houghton et al. ,1992). But it is generally believed that in the Yellow River basin, even with a slight increase in precipitatin, climate warming will trigger more evaporation resulting in a decrease of soil moisture and overalll drier conditions in the next century. Moreover, rate of soil erosion in the Loess Plateau depends more on the frequency and intensity of storm rainfall than on the amount of annual precipitation (Hu et al. ,1992;Wang and Huang,1992);and the former is much harder to predict. However, owing to the dominant role of anthropogenic effects on soil erosion in the Loess Plateau, and consequently on sediment load of the Yellow River, it seems that in predicting the sediment load of the Yellow River over the next 20～50 years, more attention should be paid to human activity than to climatic change.

Although it is difficult to predict in quantitative terms the effect of future water conservancy works and other human activities on the sediment load of the Yellow River, several changes are likely during the next 20～50 years:

(1) Increasing diversion of the river water for irrigation will result in a considerable reduction in sediment load. At present, the mean annual flow of the lower Yellow River is $437\times10^8 m^3$ and the volume of the river water diverted for irrigation and other uses is over $250\times10m^3$ per year and the associated reduction of silt about $2.2\times10^8$ tons per year. According to current plans, the irrigation area drawing water from the Yellow River may be doubled in the upper Yellow ? River basin (Ningxia and Inner Mongolia) over the next 20 years and the irrigation areas in the middle and lower Yellow River will also be expanded. Thus, a further reduction of sediment load of about $1.0\times10^8$ tons per year is likely.

(2) Construction of a series of large reservoirs on the Yellow River (six completed, two under construction, four in the planning stage) has a significant effect on the sediment load. On the upper

Yellow River, Liujiaxia and Qingtongxia reservoirs have retained about $0.7\times10^8$ tons per year of silt in their first 10 years of operation. It is expected that the largest reservoir, Longyangxia, with a capacity of $268\times10^8 m^3$ (about four times larger than Liujiaxia) retained more silt since its completion in 1989. Xiaolangdi reservoir, below Sanmenxia, will be a major silt retainer. Its construction has been set for the end of this century. When completed, it is expected to retain $3\times10^8\sim4\times10^8$ tons per year of silt throughout 20 years of operation and to result in a drastic reduction of the sediment load of the lower Yellow River.

(3) Industrial development in the upper reaches of the river, particularly development of coal mining and coal-fired power plants, will consume over $100\times10^8 m^3$ per year of water by the beginning of the next century. It is expected that about $0.5\times10^8$ tons of silt will be taken out of the river every year.

From the above, we may reasonably predict that even without taking account of future improvement of soil conservation in the Loess Plateau, annual sediment load of the Yellow River at Huayuankou near Zhengzhou will probably be reduced by about $4\times10^8\sim5\times10^8$ tons by the early years of the twenty-first century. In other words, a reduction of 30%～40% of total sediment load of the lower Yellow River will be triggered by purely anthropogenic factors in the foreseeable future.

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## Notes

[1]Sixty-two samples were analysed, each sample yielding more than 200 pollen grains (Professor C. C. Sun and C. M. Wei, Xian College of Geology, Xian, pers. comm.).

[2]Written communication from Professors N. H. Shi and S. G. Zhu, Institute of Historical Geography, Shaanxi Normal University, Xian, April 1992.

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