Investigation of soil erosion on terraced fields near Yanting, Sichuan Province, China, using caesium-137

T. A. QUINE, D. E. WALLING
Department of Geography, University of Exeter, Exeter EX4 4RJ, UK
X. ZHANG, Y. WANG
Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, PO Box 417, Sichuan 610015, China

Abstract Much of the agricultural land in the Central Hills area of the Sichuan Basin is at risk from soil erosion by water. An investigation of rates and patterns of soil erosion on agricultural land near Yanting was undertaken using the caesium-137 technique. Erosion of the upper parts of sloping fields was found to be severe, with rates of the order of 20 to 50 t ha^{-1} $year^{-1}$. However, infield deposition and sediment retrieval from field ditches has led to low net soil loss from the fields with rates of the order of 1 to 6 t ha^{-1} $year^{-1}$. These data suggest that traditional soil conservation strategies are providing effective protection of much of the cultivated land, but the high potential for soil erosion must be recognized if any change is made in land use or management.

THE CONTEXT

The Sichuan basin of China includes six million hectares of cropland and is one of the most populous agricultural regions in the world. The basin can be divided into three zones; the Chengdu Plain, the Central Hills and the Eastern Parallel Ranges. The Central Hills, which occupy the largest area, have two urgent land management requirements (Zhao, 1986), namely the improvement of the irrigation systems and more effective control of soil erosion. The development of more effective erosion control strategies must be based on improved understanding of the problem and there is a need for basic information on the rates and patterns of soil loss involved. An attempt has been made to explore the potential for using the caesium-137 technique to assess soil erosion in the area.

The caesium-137 (^{137}Cs) technique for assessing soil erosion has now been applied in a wide range of environments, and the basis of the technique is well documented (cf. Wise, 1980; Campbell, 1983; Campbell *et al.*, 1988; Walling & Quine, 1990a, 1991). However, relatively few studies have been undertaken outside the temperate regions of the world and in less developed agricultural systems. Therefore, the work in the Sichuan basin reported here also provides an opportunity to examine the potential of the technique in a different suite of climate-land use conditions.

The study area

The location of the study area and the topography of the sampling site are shown in Fig. 1. Yanting lies in the region of horizontal, interbedded Upper Jurassic reddish sandstones and purple mudstones (Peng Lai Zhen group) which characterize much of the Central Hills of the Sichuan basin. The region, which has an elevation of 250-650 m, has been dissected by numerous river valleys to produce mesa topography. The sampling site (Fig. 1(c)), which has been chosen as representative of the general terrain of the area, comprises a flat summit bordered by steep slopes broken by natural terraces. The average inclination of the slopes is about 20°, but the steeper slopes underlain by the

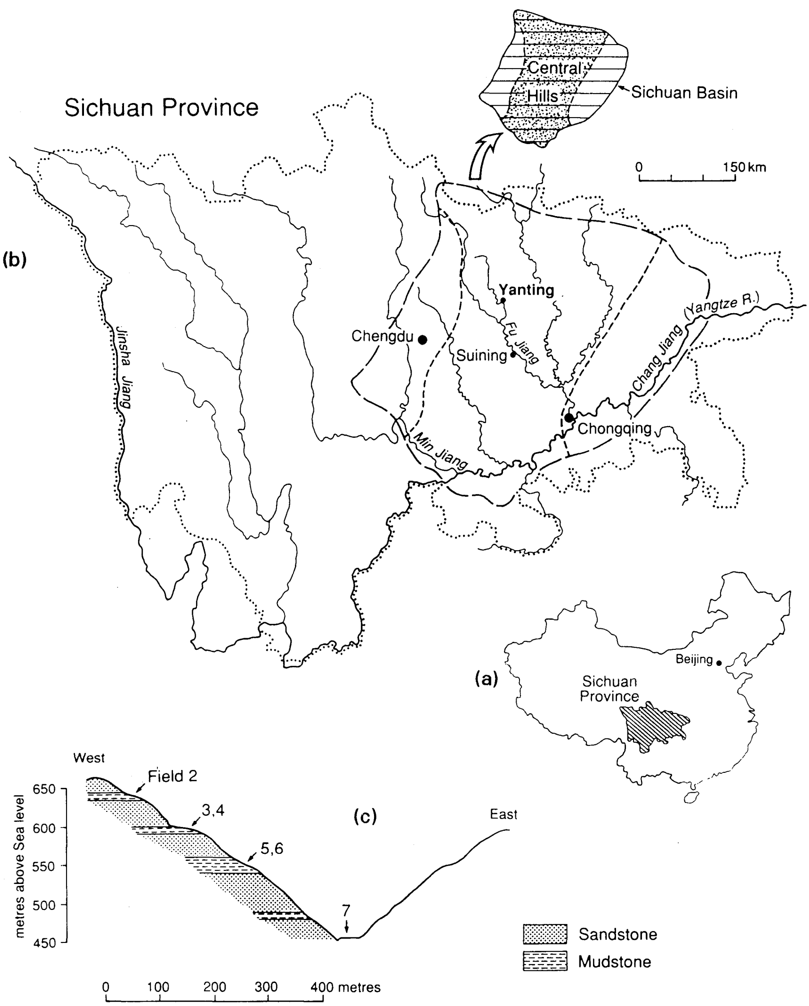

Fig. 1 Location and topography of the study site:
(a) Location of Sichuan Province.
(b) Location of the Yanting study site in the Central Hills region.
(c) Cross-valley transect and geology of the study site.

sandstones are characterized by angles in excess of 40° whilst the natural terraces underlain by mudstones exhibit slopes of less than 15°. More than 2000 years of cultivation have resulted in the complete removal of the original subtropical evergreen broad-leaved forest. The steep slopes are now mantled by very thin coarse soils supporting grasses and scattered cypress and oak trees which provide wood for building and burning and grazing for cattle and pigs. The cultivated land is almost entirely limited to the gentle terrace slopes, where the mudstones weather rapidly to form fertile purple lithomorphic soils. The valley floor and gentle footslopes are occupied by paddy fields.

The Central Hills region is the warmest part of the Sichuan basin during winter, with a mean January temperature of 6°-8°C. The summer is long and hot with a mean July air temperature of 26°-29°C, and the mean annual temperature is 17.4°C. Frost-free days average 312 per year, and the mean annual precipitation ranges between 900 and 1100 mm, with an annual maximum of 1436 and minimum of 709 mm. This climate provides the potential for two crops per year with harvests in May and October. During the dry winters, the main crops are rape and wheat grown both on the valley floors and on the sloping terraces. During summer rice is grown on the irrigated valley floors and footslopes, and the main crops on the sloping cultivated land are sweet potatoes and maize.

In an agricultural context, soil is most susceptible to erosion when crop cover is minimal. The period from harvest to the establishment of ground cover by the new crop is therefore the most critical. If this period is characterized by high precipitation intensities, there is an increased risk of erosion. In the study area, the period following the October harvest is marked by low rainfall intensities and less than 10% of the annual total falls between November and January. In contrast, the period following the May harvest is characterized by high intensity rainfall, with a daily maximum of 196 mm, and as much as 40% of the annual total may fall between June and August. Cultivated land in the Central Hills area is, therefore, very susceptible to water erosion during the summer months. Where soil protection measures are not employed, sheet and rill erosion may be very severe and the Laboratory of Pedology of the Chengdu branch of Academia Sinica estimate that rates of erosion on cultivated land in the Yanting area approach 10 t ha^{-1} $year^{-1}$.

Soil protection and traditional cultivation

Many of the traditional cultivation practices employed in the Yanting area embody soil protection benefits, possibly as a result of conscious adaptation to the high erosion hazard. Slope length and angle are frequently controlled by subdividing the natural terraces into several fields. In some locations, channels have been constructed above the upslope edge of fields to divert runoff from the adjacent steep uncultivated slopes into settling ponds, where both sediment and water are stored for later retrieval. Ditches constructed at the upper and

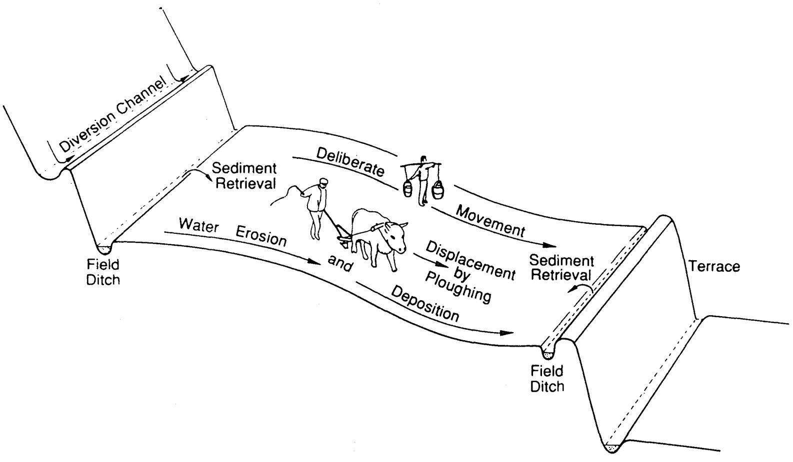

Fig. 2 Schematic diagram of soil conservation measures and processes of soil redistribution in a terraced landscape at Yanting.

lower margins of the fields are regularly maintained by returning deposited sediment to the field (Fig. 2). Cropping practices, such as subdividing the fields into 1 m-wide strips of maize and wheat (where the strips lie across the slope), or planting rape seedlings by hand in preformed hollows will also have soil conservation benefits. Furthermore, the absence of compaction by heavy machinery and the regular application of organic manure help prevent the destruction of soil structure which is a severe problem in many areas of mechanized agriculture.

Despite these beneficial practices, soil erosion and deposition by water still occur in combination with downslope displacement of soil during ploughing (Fig. 2). Additional downslope translocation may be caused by deliberate movement of soil from the upper parts of fields to the lower-lying areas (Fig. 2). The potential impact of these additional processes upon ^{137}Cs redistribution must be recognized when estimating erosion rates.

THE METHOD

The caesium-137 technique

Caesium-137 is an artificial radionuclide with a half-life of 30.17 years which was produced as a by-product of past atmospheric testing of thermonuclear weapons. The ^{137}Cs was released into the stratosphere, distributed globally and deposited as fallout, usually in association with precipitation. Its value as a sediment tracer lies in its high affinity for soil particles, especially the clay fraction (Bachhuber *et al.*, 1982; Livens & Baxter, 1988), such that in most agricultural environments lateral redistribution after deposition takes place only in association with sediment. Assessment of ^{137}Cs redistribution is commonly based upon comparison of measured inventories (total activity per unit area) from the sampled site with an equivalent estimate of the cumulative atmospheric deposition. As direct measurements of atmospheric deposition to a site are rarely available, the cumulative input or reference inventory is established by sampling nearby undisturbed, uneroded locations supporting permanent grassland. Where sample inventories are lower than the local reference level, loss of ^{137}Cs-labelled soil and therefore erosion may be inferred. Similarly, sample inventories in excess of the reference level are indicative of addition of ^{137}Cs-labelled soil by deposition. The magnitude and direction of measured deviations from the local reference level provide a qualitative assessment of sediment redistribution.

In order to derive quantitative estimates of rates of soil erosion and aggradation from ^{137}Cs measurements, it is necessary to establish empirical or theoretical relationships between the magnitude of the deviation from the reference inventory and the extent of soil loss or gain. As empirical calibration data are rarely available, the authors have developed a numerical model which represents the redistribution of ^{137}Cs in association with erosion and aggradation (Quine, 1989; Walling & Quine, 1990b). This model can be used to simulate the effect of a range of long-term erosion and aggradation rates upon the ^{137}Cs inventory of soil profiles and such data are then used to derive calibration relationships.

The approach

The approach outlined above was devised for use in agricultural areas where the dominant causes of soil movement are erosion, deposition and tillage. Slight modifications were employed in this study where other human activities (Fig. 2) may exercise an important impact upon the nature and extent of soil redistribution. In particular, deliberate addition of soil to low-lying areas and retrieval of soil from field ditches may complicate the relationship between rate of aggradation and increase in the ^{137}Cs inventory predicted by the model. As a result, information on the profile distribution of ^{137}Cs, as well as the overall inventory, was obtained by subdividing the core samples into 5 or 10 cm thick sections, and analysing the sections separately. This allows the rate of aggradation to be estimated from the depth below the plough layer at which measureable concentrations of ^{137}Cs are found.

All analysis for ^{137}Cs was undertaken on soil samples collected using a steel core tube of 9.7 cm diameter, which was driven into the ground using a sledge hammer. The samples were air-dried and then separated into weighed fractions larger and smaller than 2 mm. Measurements of ^{137}Cs activity were made on the <2 mm fraction by gamma spectrometry, using a coaxial germanium detector and multi-channel analyser system. ^{137}Cs was detected at 662 keV and the counting times, typically 25 000 to 50 000s, provided results with an analytical precision of $\pm 6\%$ (2SD). Gamma spectrometry provided measures of ^{137}Cs activity per unit mass (mBq g^{-1}) which were combined with sample weights and core dimensions to provide ^{137}Cs inventories (mBq cm^{-2}).

THE RESULTS

Caesium-137 data from the study area

Sectioned core samples were collected from undisturbed grassland on the flat summit of the hill above the sampled fields (Fig. 1(c)) and from another flat hill top within 3 km of the sample site. As expected, the ^{137}Cs profile distributions from these sites evidenced a sharp decline in activity from the surface and, on the basis of the measurements undertaken on the cores, the reference inventory was estimated at 260 mBq cm^{-2}. Further sectioned core samples were collected along downslope transects from seven fields. However, one of these was later found to have been cultivated for only 10 years with an unknown previous history, and this field has therefore been excluded from the discussion. The position of the sampled fields on the overall slope transect is indicated on Fig. 1(c) and the topography of the individual fields and the location of the core samples is shown in Fig. 3. The ^{137}Cs profile distributions, showing the activity in mBq g^{-1} for each section of a core sample, are also presented in Fig. 3 for all sample locations.

As the maximum depth of cultivation at the site is 20 cm, it was initially considered that a sampling depth of 35 cm would be sufficient to include all the ^{137}Cs within a soil profile. This was found to be the case where the point inventory was less than the reference level, indicating that erosion had taken place. However, at some depositional locations, indicated by high inventories and stretched profiles, ^{137}Cs-bearing soil extends below 35 cm and it has not been possible to identify the total point inventory. Despite this limitation, it is possible to identify a clear pattern of erosion on the upper parts and deposition in the lower zones of all the sloping fields. In most cases, the change from erosion to deposition occurs near the mid-point of the field, but in field 4L (4 lower) only *c.* 25 % of the field length is subject to erosion.

When the individual profiles are examined in greater detail three groups may be identified. The first group includes those profiles which conform to the expected pattern, whereby, at sites with an inventory lower than the local reference level, ^{137}Cs is not found below the maximum depth of cultivation (20 cm), and, at sites where the sample inventory exceeds the local reference level, relatively high activities are recorded from the surface to depths well below the plough layer. This first group includes all the profiles from fields 3 and 5, profiles 2 to 8 of field 4, profiles 1, 2 and 4 of field 2, and profiles 2, 5 and 7 of field 6. Similarly, all the profiles from field 7 fall into this category, because the slight extension of profile 4 is probably due to its deeper cultivation during the wet season when it is used as a paddy field. This would be consistent with the almost constant activity to 30 cm seen in profiles 1 and 2 from the same field.

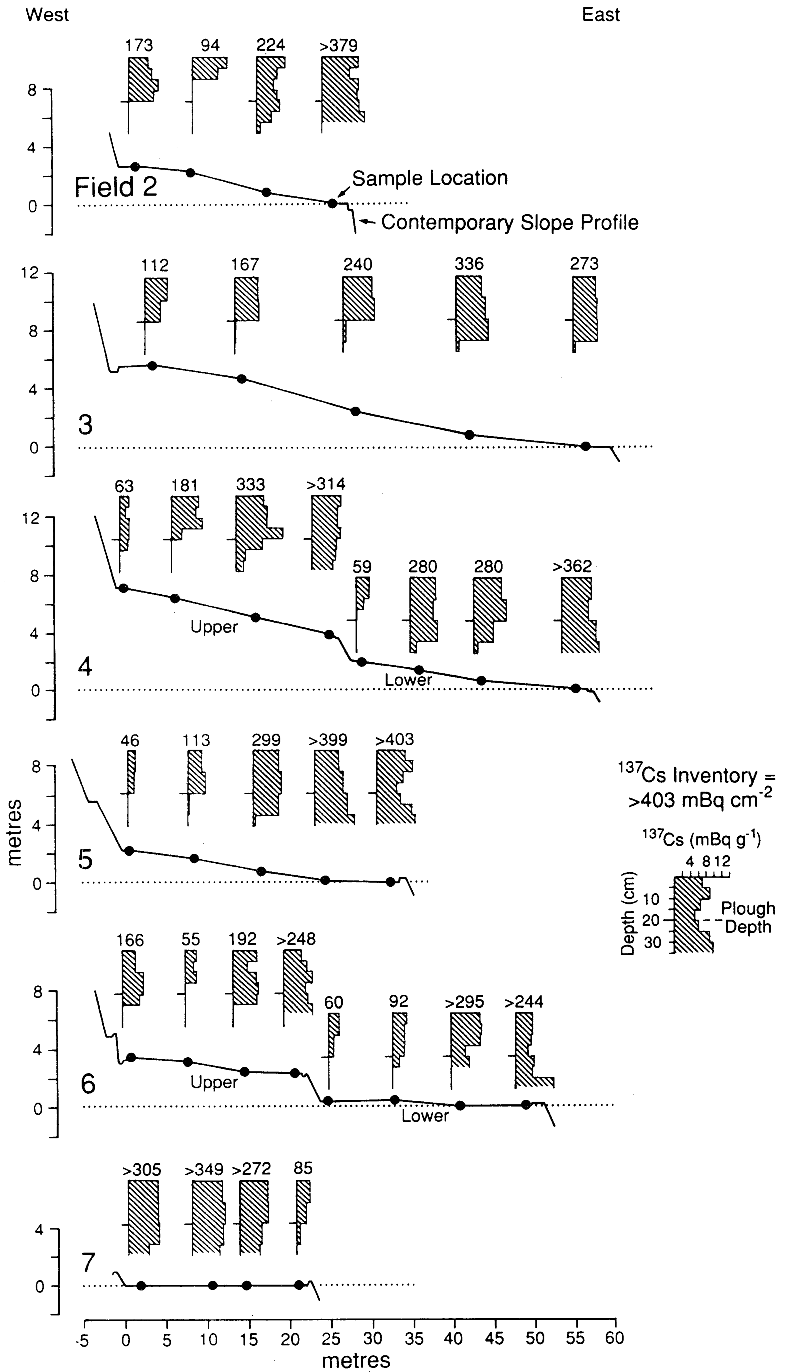

Fig. 3 Slope profiles, sampling locations, caesium-137 inventories and depth distributions for the sampled fields, near Yanting.

The second group includes profile 3 of field 2, profile 1 of field 4, and profiles 1, 3 and 6 of field 6. These profiles show extension of the ^{137}Cs distribution below the depth of cultivation, despite displaying a total inventory significantly lower than the local reference level. Two possible explanations may be identified to account for this feature. These involve either a local increase in the depth of cultivation or the addition of sediment with a low ^{137}Cs activity to an eroding site. The second explanation could be linked to the spreading of deposited sediment removed from the field ditches (Fig. 2), and this is favoured for profile 1 of field 4 and profile 1 of field 6, both of which are adjacent to field ditches. Similarly the extension of the ^{137}Cs distribution below 30 cm at profile 3, field 2, is not readily explained by increased depth of cultivation in view of the limited depth of profiles 1 and 2. It seems more probable that this is an eroding site where some attempt has been made to reduce the local slope angle by importing soil from the upslope area, already depleted in ^{137}Cs, thereby increasing the depth of the distribution without greatly increasing the inventory. This explanation may also be applied to profiles 3 and 6 of field 6, which will be discussed further in relation to profiles 4 and 8 of the same field.

The third group comprises profiles 4 and 8 from field 6, which evidence distributions which extend well below the depth of ploughing and continue below the depth of sampling. These are further characterized by an inventory for the upper 35 cm of the profile which is close to the local reference and a relatively low activity of ^{137}Cs in the plough layer. These locations appear to be depositional sites, where profile extension through gradual aggradation has been increased by addition of large quantities of ^{137}Cs-depleted soil, either from the adjacent field ditch in the case of profile 4 or from upslope locations. A similar explanation has already been invoked to explain the extension of profiles 3 and 6 from the same field, suggesting widespread application of soil over the lower part of the two terraces of field 6. Although the basic terrace structure has existed for more than 40 years, the profile evidence suggests that some further levelling has been undertaken during the period after the bulk of the ^{137}Cs had been deposited and subjected to erosion and aggradation. It is possible that this may have occurred at the end of the Cultural Revolution, when the land reverted from communal to individual management.

Rates of erosion

In order to obtain estimates of erosion rates from the ^{137}Cs measurements presented above, the model developed by Walling & Quine (1990b), and referred to previously, was employed to produce a calibration relationship. This relationship was employed directly to estimate erosion rates at eroding locations in the first group of profiles discussed above. For those profiles in the first and third groups evidencing aggradation, the rate of aggradation (t ha^{-1} $year^{-1}$) was obtained by estimating the total depth of aggradation (cm) and dividing this by 36 (the number of years from 1954 to the date of sampling, 1990) and multiplying the result by 100 (assuming a bulk density of 1 g cm^{-3}). The total depth of aggradation was estimated by taking the distance between the base of the cultivation layer (20 cm) and the mid-point of the deepest ^{137}Cs-bearing section of the core. If the bottom section of the core contained appreciable levels of ^{137}Cs, this was used to provide a minimum estimate of total aggradation. For those profiles in group 2 where the inventory value indicates erosion, but soil addition has caused an extension of the profile, a combination procedure was employed. The erosion rate was estimated using the model-derived calibration relationship, and this was subtracted from the depth-derived aggradation rate.

Using these procedures it was possible to estimate the point erosion and aggradation rates for each sampling location. The point rates may be used to determine the impact of erosion and aggradation upon the slope form, and Fig. 4 compares the current slope profile with an estimate of that for 1954. Field 7, which is used as a paddy field, is clearly exceptional in that it has been subject to aggradation over most of the area. This is probably a result of sediment warping during the summer months. The high field boundaries which retain the irrigation water would also effectively trap the sediment load. When examining the sloping fields, it is necessary to consider a range of processes and impacts in order to interpret changes in the slope profiles. These include the role of runoff generation both within the field and from the steep sandstone slopes above the mudstone terraces and the role of ploughing in displacing soil downslope. Where downslope displacement by ploughing is the dominant process, the expected pattern would be peak soil loss at the upslope edge of the field, low values downslope and accretion at the base of the field. Similarly, runoff generated on the slopes above the field could be expected to have maximum impact at the upslope edge of the field. In contrast, in-field generated runoff could be expected to increase in volume downslope and soil loss would therefore tend to increase with slope length. Deposition of eroded soil would be expected where the slope angle decreases at the base of the fields. Clearly these patterns could be altered or accentuated by any deliberate levelling of the fields, as discussed in the previous section.

When the slope profiles are examined in the light of these predicted patterns, it is evident that a distinction may be made between fields 2 and 6U (6 upper) and the remaining sloping fields. Fields 3, 4U, 4L, 5 and 6L show a downslope decline in the depth of soil eroded, with maximum loss at the top of the field. This pattern suggests that the dominant causes of soil redistribution are downslope displacement by ploughing and erosion by runoff generated on the steep slopes above fields 3, 4U and 5.

In contrast, the slope profiles of both field 2 and the upper part of field 6 show an increase in soil loss over the first 8 m of the field, with low levels at the upper edge. These lower levels of soil loss at the upper edge of the field may reflect reduced runoff reaching the fields from the steep slopes above. Field 2 lies on a small terrace only 15 m below the summit of the hill (Fig. 1(c)) and therefore has a limited catchment area, and the upper edge of field 6 is protected by a diversion channel (Fig. 3), which will prevent the majority of runoff generated on the steep slope above from reaching the field.

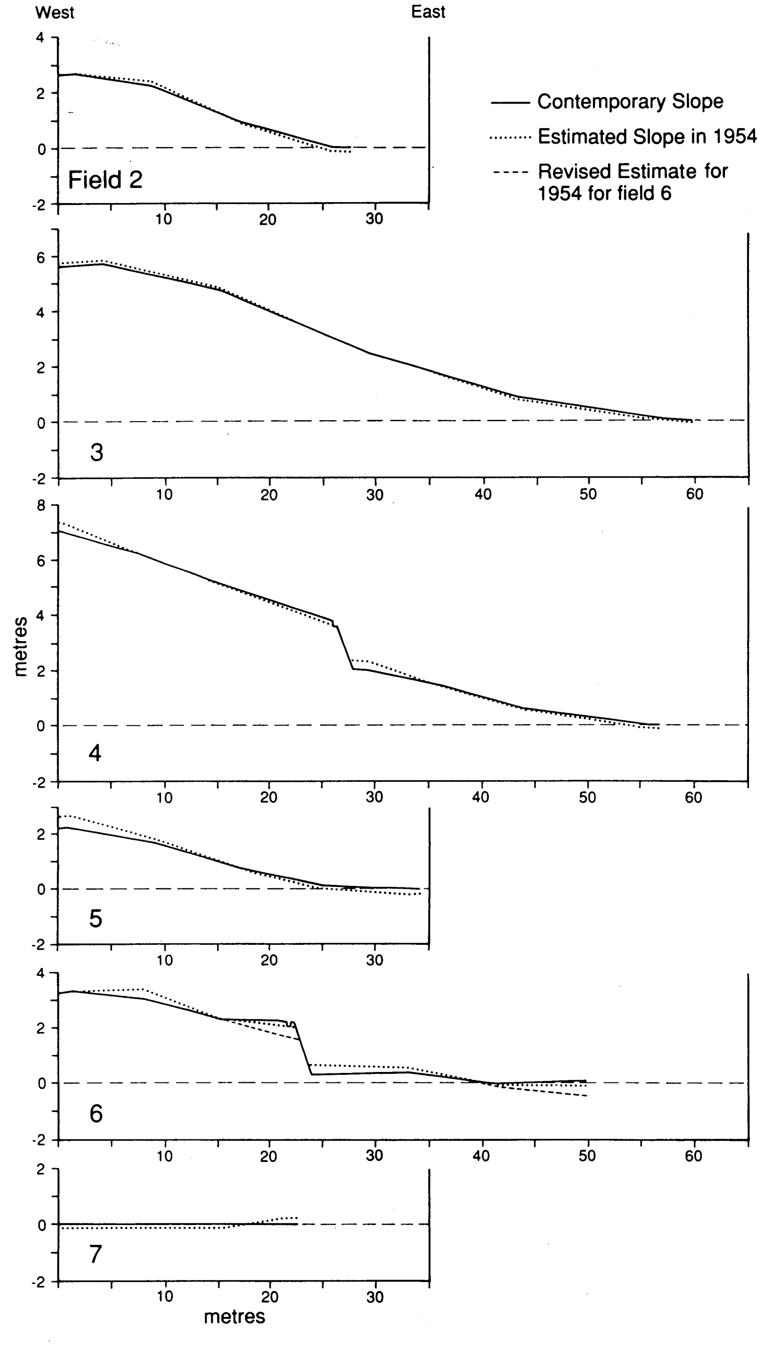

Fig. 4 The pattern of erosion and aggradation illustrated by comparison of the contemporary slope profiles with their estimated form in 1954. The two estimates for field 6 are discussed in the text.

However, the impact of downslope displacement by ploughing is seen in the existence of measureable soil loss at these protected locations (9 t ha^{-1} $year^{-1}$

for field 2, and 5 t ha^{-1} $year^{-1}$ for field 6). The increase in the depth of soil loss down the field is consistent with erosion induced by runoff generated within the field, but the very high rates identified suggest that deliberate levelling has also occurred. Similarly, although downslope displacement by cultivation may be responsible for some of the soil loss at the upper margin of fields 4L and 6L, the high rates of soil loss seen at these locations are probably also a result of deliberate levelling.

Field rates of soil loss

Estimates of erosion rates for each field are listed in Table 1. These were established by integrating the point data along the slope transects. The gross rate of erosion is equal to the mass of soil eroded each year within the field (some may be redeposited inside the field) divided by the field area; the mean rate is equal to the mass of soil eroded each year within the field divided by the area of the field subject to erosion; the net rate of erosion is defined as the mass of soil exported from the field each year divided by the field area; the sediment delivery ratio is equal to the net rate divided by the gross rate, expressed as a percentage (if all eroded soil was exported from the field the delivery ratio would equal 100%, if all was redeposited within the field the ratio would equal 0%).

Before considering the integrated data in detail, it is important to recognize one limitation, namely that where ^{137}Cs was found in the deepest section of a core it was only possible to make an estimate of the minimum depth of aggradation. This has no effect upon the estimates of mean and gross erosion rate, but it will influence the estimate of net soil loss and the sediment delivery ratio. The most problematic case is undoubtedly field 6 where rates of aggradation may have considerably exceeded the minimum estimates employed.

The estimates of mean and gross soil loss provide an indication of the severity of erosion on the studied fields. The gross rates of erosion estimated for fields 2, 3 and 4 (9.0 to 14.3 t ha^{-1} $year^{-1}$) are closely in line with the estimated erosion rate of 10 t ha^{-1} $year^{-1}$ suggested by the Laboratory of Pedology of the Chengdu branch of Academia Sinica. In conjunction with the higher rates estimated for fields 5 and 6, these data demonstrate the importance of soil erosion in this locality. This is further confirmed by the mean rates of soil loss from the eroding areas which vary from 18 to 62 t ha^{-1} $year^{-1}$. Soil loss of this magnitude could be expected to exert a significant effect on productivity, despite the high rate of soil formation. However, the high rates of manure application may mask the impact of erosion.

Although the estimates of mean and gross rates of soil loss highlight the severity of the erosion problem, identification of rates of actual soil loss from the fields require an assessment of sediment redeposition. This is very difficult to obtain using conventional approaches, such as erosion plot studies, but is

Table 1 Integrated field measures of erosion.

(Values for field 7 have not been listed because this field was subject to addition of sediment by warping. The first values for field 6 were obtained using a minimum estimate of aggradation and the derivation of the revised values is discussed in the text.)

Field	Erosion rate (t ha^{-1} year^{-1}):			Sediment delivery
	Gross	Mean	Net	Ratio (%)
2	13.1	22.1	6.60	50.4
3	9.0	18.2	0.73	8.2
4U	13.7	34.5	1.11	8.1
4L	14.3	54.3	−1.00	−7.0
4			0.02	
5	25.9	61.9	4.06	15.7
First values				
6U	29.1	43.5	22.80	78.3
6L	33.7	53.5	23.17	68.8
6			23.00	
Revised values				
6U	29.1	43.6	4.71	18.3
6L	33.7	53.5	3.65	11.3
6			4.14	

readily achievable using the ^{137}Cs technique. The significance of redeposition may be seen in the net rates of soil loss which, varying from 0.02 to 6.60 t ha^{-1} year^{-1} for fields 2 to 5, are clearly much lower than the gross rates and the Laboratory of Pedology estimate of 10 t ha^{-1} year^{-1}. The low net rates reflect both the potential for within-field redeposition, seen most clearly in the basal zone of field 3, and the effectiveness of soil conservation measures in trapping sediment and of human activity in returning it to the fields.

Only field 6 appears to have a high net rate of soil loss, and as indicated above this may be due to the use of a minimum estimate for the rate of aggradation associated with profiles 4 and 8 from this field. In the preceding sections it has been suggested that field 6 may have been subject to recent deliberate levelling. If this is the case, then deposition of sediment at the base of each part of the field could have produced a very high rate of aggradation. If an estimated depth of aggradation of 50 cm at the downslope margins of both 6U and 6L is used, then the net rates of soil loss and the sediment delivery ratios are found to be in line with the values found in fields 2 to 5 (net rate = 4.71, 3.65, 4.14 t ha^{-1} year^{-1} for 6U, 6L and 6 whole; sediment delivery ratio = 18.3 and 11.3% for 6U and 6L, respectively). The changes in slope profile associated with these rates are illustrated in Fig. 4, which confirms the feasibility of the estimates.

The efficiency of the soil conservation measures is further reflected in the low sediment delivery ratios. If the revised estimates for field 6 are employed, then only field 2 has a sediment delivery ratio in excess of 20%.

While this may reflect underestimation of aggradation, the absence of either an extensive zone of low slope angle or a ditch and bank at the base of the field could be expected to result in a reduced capacity for sediment redeposition and retrieval. Overall, however, the evidence from the remaining fields suggests that existing soil conservation measures and cultivation practices provide an effective counter to soil transport from the cultivated areas.

CONCLUSION

The combination of climatic and topographic conditions and agricultural practice render the cultivated soils of the Yanting area very susceptible to erosion by water. Use of the ^{137}Cs technique has confirmed that this susceptibility is reflected in high gross rates of erosion, on sloping cultivated fields, which may exceed 10 t ha^{-1} $year^{-1}$. These rates are in line with estimates produced by the Laboratory of Pedology of the Chengdu branch of Academia Sinica. However, use of the ^{137}Cs technique has generated previously unavailable information regarding sediment deposition within the fields. These data demonstrate that net rates of soil loss from the fields are much lower, and of the order of 1 to 6 t ha^{-1} $year^{-1}$. In most cases less than 20% of the eroded sediment is transported from the cultivated land. This suggests that the traditional soil conservation measures are providing effective protection of much of the cultivated land and limiting potential pollution of water courses by agricultural sediment. However, if changes towards more mechanized agriculture are planned, the potential for very severe erosion must be recognized and existing soil conservation measures and practices should be retained or further developed.

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