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Erosion due to cultivation of calcareous clay soils on hillsides in south-west France. II. Effect of ploughing down the steepest slope

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The erosion of calcareous clay soils from Terrefort in south west France is not exclusively due to run-off water. An experiment was carried out in situ to quantify the effect of ploughing on the displacement of soil down the slope. In a field experiment, a trench $0.4\text{ m} \times 0.4\text{ m} \times 20\text{ m}$ was dug parallel to the contours and filled with crushed gravel. Gravel distribution on the surface and within the soil mass was examined after ploughing downhill and then uphill. Mathematical analysis of the data showed that a much greater total soil mass was displaced downwards by ploughing downhill than by ploughing uphill. This resulted in soil removal from the top of the plot ($0.32\text{--}1.62\text{ kg m}^{-2}$ for a single ploughing) and much greater accumulation at the base of the slope than estimated for surface water erosion (i.e. $0.04\text{--}0.25\text{ kg m}^{-2}\text{ year}^{-1}$), according to measurements made by other authors in the same region.

Keywords: Erosion; Soil on slope; Tillage; Field experiment; Ploughing

1. Introduction

The soils on the hillsides of south west France have developed on impermeable Tertiary sandstone. Downcutting by rivers since the end of the Tertiary has produced a hilly relief (Revel, 1982) in which the soil's spatial organisation with regard to chronosequence and toposequence is highly complex. Revel and Rouaud (1985), Rouaud (1987) and Revel et al. (1990) showed that run-off water was not the only erosive agent and that cultivation techniques have contributed strongly to downward soil displacement. The present mesorelief and eroded areas may be explained from a model based on the ancient contour ploughing

method, in which the soil was tipped over and downwards (Revel and Guiesse, 1995).

After mechanisation, ploughing had to be carried out in the direction of the slope. The low power of the first tractors only permitted downhill ploughing, which resulted in soil accumulation at the base of the plot. When ploughing is performed under ideal moisture conditions, the soil's structural stability should, in theory, ensure sufficient cohesion of the aggregates to allow the ploughed portion to be overturned on the spot without any isolated particles or small aggregates being displaced down or up the slope according to the direction of ploughing. Because of their velocity, the implements used during ploughing project some of the aggregates in the direction of movement. When the tractor goes downhill, a weight effect adds to this phenomenon, whereas the effect is curtailed in the uphill direction. Ploughing such soils leads in the long term to downward displacement of soil towards the base of the slope. It is this phenomenon that we intend to quantify here.

2. Material and methods

2.1. Choice of tracer

To examine the effect of ploughing on soil displacement down the slope, a tracer has to be introduced homogeneously into the soil above a reference level, at a known concentration, and to a depth at least equal to that of ploughing. Choice of the tracer presents several difficulties. Whether the tracer is a particulate material or chemical compound, radioactive or not, it must not be transported in suspension or in solution by rainwater. Subsequent extraction of the tracer from the soil and its determination should also be easy. Use of a solid tracer poses the problem of homogenisation. Numerous large aggregates exist in clay soils and, if these are crushed to ensure good tracer distribution, the structure and mechanical properties of the final material no longer have anything in common with those of the soil in situ. The same problem of homogenisation is encountered if the tracer is dissolved in a stable organic solvent, insoluble in water. The organic solvent may also considerably modify soil structure (Henin, 1960).

Despite numerous trials, an ideal tracer that fits all of these criteria has not been found. We finally selected crushed siliceous gravel 4–6 mm in diameter, that we put in a trench. The soils under test did not contain any such material.

2.2. Experimental conditions

The experimental plot was situated on a hillside with a uniform slope of 11°. The soil was a calcic cambisol (according to FAO taxonomy) with a sandy clay loam texture, high organic matter content for the region (17 g kg⁻¹) and high structural stability ($I_s=0.5$; Henin, 1960). A trench was dug parallel to the contour, the dimensions (0.4 m × 0.4 m × 20 m) dictated by the experimental conditions: the length of 20 m was a multiple of the machine width, the depth of 0.4 m was slightly greater than the ploughing depth, and the width of 0.4 m corresponded to the dimension of the mechanical digger scoop used to prepare the trench.

First the soil was taken out of the trench and removed from the plot. The trench was then filled with gravel after protecting the surrounding soil with tarpaulin to avoid contamination. Traditionally, the soil is ploughed both uphill and downhill along the steepest slope. Thus the estimated amount of soil displaced downwards is the difference between the volume of soil displaced downhill and the volume of soil displaced uphill. We therefore carried out two treatments on 12 m widths. The first treatment was a single downhill ploughing which was carried out with a Huard plough with three frames and five shares 0.4 m apart, drawn by a Fiat tractor 980 DT 100 hp, at a speed of 7 km h⁻¹. The estimated ploughing depth was 0.3 m. The second treatment, a single uphill ploughing with speed reduced to 6.2 km h⁻¹, was carried out nearby. After ploughing the soil was rolled and levelled with the tractor to facilitate sampling. Then, we sampled the soil surrounding the trench to quantify the gravel displacement due to both the treatments, uphill and downhill ploughing.

2.3. Mode of sampling

First, gravel displacement in the trench due to ploughing was initially observed on the soil surface. A visual, systematic count was made on the soil surface, using 5 cm square quadrats. Complete analysis requires a consideration of the mass of soil. For this, depth samples were taken from positions where the surface distribution was about average. To avoid the effect of position in relation to passage of the tractor, rectangular parallelepipeds with lengths equal to the distance between two ploughshares (0.4 m) were sampled. The samples were 0.1 m in height and 0.1 m in width so as to provide samples of reasonable weight for data analysis. Each sample was weighed then sieved to determine the weight of the constituent gravel (P_g). The nature of these operations precluded replication in the initial phase. The total bulk densities of the gravel ($D_g = 1.33 \text{ Mg m}^{-3}$) and soil ($D_t = 1.63 \text{ Mg m}^{-3}$) were measured to calculate the soil weight equivalent (P) of the gravel. The need for corrections for water content was circumvented by measuring densities D_g in the field moist state. To convert our results to a dry soil, D_t was measured in the dry state.

$$P = P_g(D_t/D_g) \text{ in kg } (S_{we}) \quad (1)$$

The sum of all the P values gave the weight of the gravel carried out of the trench, expressed in soil weight equivalent (S_{we}).

2.4. Limits of the experimental protocol

First, to determine the total amount of soil displaced across a reference level, the tracer should have been introduced into a soil strip that was at least as wide as the maximum displacement of the particles. To correct for this, a mathematical model was used to extrapolate the results obtained for a width of 0.4 m to a strip in which the width was equal to the greatest distance covered by the gravel. Second, the texture, structure and mechanical properties of the gravel differed considerably from those of the soil. The particulate nature of the gravel certainly amplified the effect of implements on particle migration. This experiment nevertheless provides an upper estimate of the degree of downward soil displacement due to ploughing. Finally, the trench produced a discontinuity in the mechanical resistance

to passage of the implements. Because of the difference between the mechanical behaviour of soil and gravel we reduced the trench width as much as possible.

3. Results

3.1. Surface gravel distribution

The observations of gravel displacement on the soil surface showed that the upward and downward displacements of gravel were clearly defined and could attain considerable distances from the sides of the trench (2.2 m with downhill ploughing and 1.4 m with uphill ploughing). A greater quantity of gravel was displaced downward than upwards. Considerable erosion would thus occur if ploughing was carried out solely down the slope and this would not be compensated by uphill passage of the same implement.

3.2. Gravel distribution within the soil mass

3.2.1. Sampling results

First, we examined the results in each horizontal soil layer at 0–0.1, 0.1–0.2 and 0.2–0.3 m depths. This gave a random distribution from the trench (Revel et al., 1990, 1993). Such considerable dispersal of the gravel could be explained by the displacement of particles in all three spatial directions. To suppress vertical variability, the sum of the amounts of gravel found at three different depths (0–0.1, 0.1–0.2, and 0.2–0.3 m) was considered as a function of distance from the trench. The results represented in Fig. 1 exhibit a modal distribution which is a function of distance from the trench. Before continuing the data analysis, the reliability of the measurements was tested by verifying that the total volume of gravel sampled after one uphill ploughing (T_m) and one downhill ploughing (T_d) corresponded to the volume of gravel initially placed in the trench (T). This gave

$$T_m = 0.045 \text{ m}^3$$

and

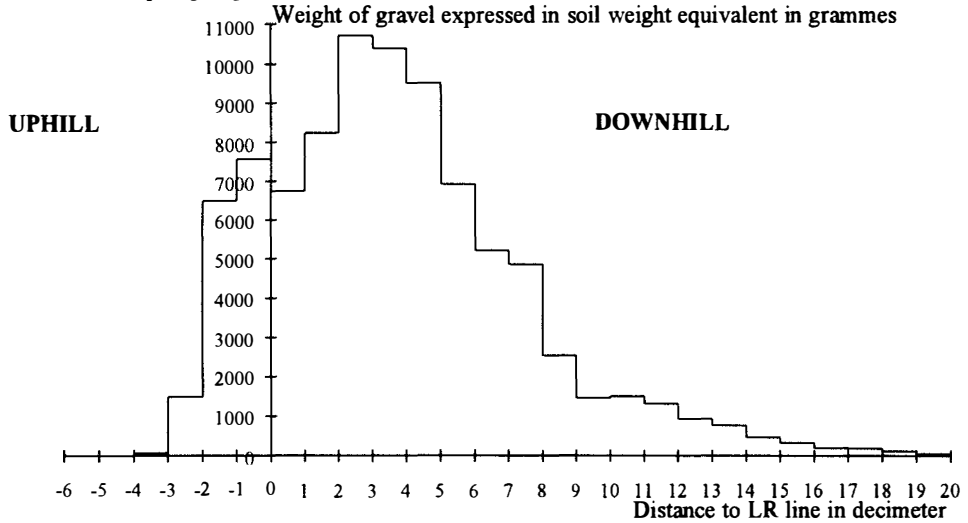
$$T_d = 0.054 \text{ m}^3$$

while

$$T = (0.4)(0.4)(0.3) = 0.048 \text{ m}^3$$

The difference between T_m and T , and between T_d and T reflected the degree of accuracy of the measurements (6% and 12% respectively). This result was considered satisfactory given the experimental conditions. Fig. 1 shows that the gravel migrated further within the soil mass after downhill ploughing than after uphill ploughing. Using Eq. (1), we calculated the sum of all P values, and so we found the mass of soil displaced without any extrapolation. The results are given in Table 1.

A : Downhill ploughing



B : Uphill ploughing

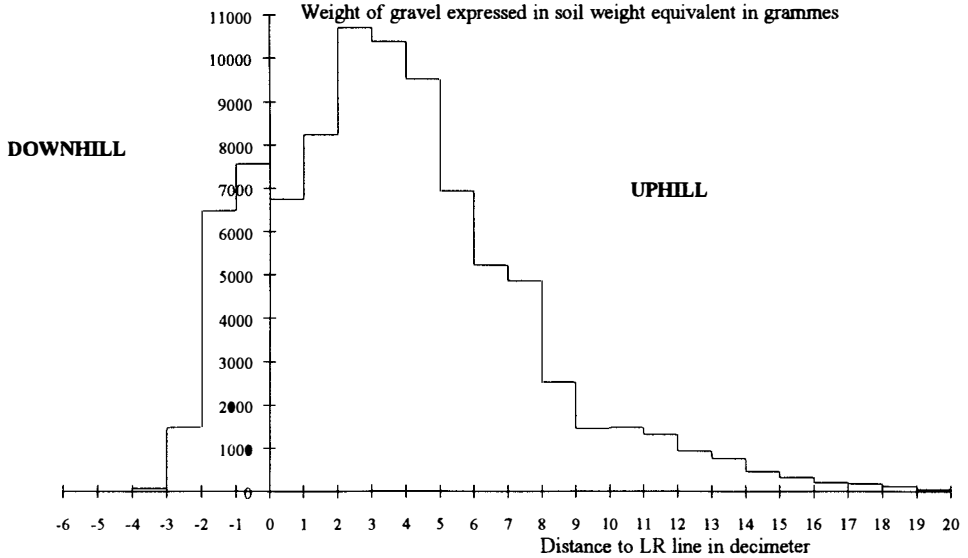


Fig. 1. Gravel distribution in the mass of soil either side of the trench after downhill ploughing (A) and uphill ploughing (B) as a function of distance from the reference line LR, which was the lower or upper limit of the trench, respectively.

3.2.2. Extrapolation of the results

The objective of this work was to determine the total mass of soil (M) displaced under the effect of implements across a linear metre in relation to a reference line (LR). In this experiment, the reference line (LR), in the case of downhill ploughing, was the lower limit

Table 1

Mass of soil (kg) displaced along the slope by one downhill ploughing and one uphill ploughing with and without extrapolation

	Without extrapolation	With extrapolation
Downhill ploughing	181.5	306.8
Uphill ploughing	110.3	144.6
Difference	71.2	162.2

of the trench, and the upper limit in the case of uphill ploughing. As the samples had been taken over a width (L) of 0.4 m, the factor $1/L$ was applied to convert the results to a strip 1 m in width for later use in comparisons with other implements.

It is apparent from Fig. 1 that the particles exhibited variable displacement. Some moved a long distance, others remained nearer the trench. Thus, at a given point, the sampled soil contained undisplaced soil, displaced gravel, and also soil from above the point under consideration. Finally, all particles which migrated at most 0.4 m were counted in this experiment as the soil was marked over a distance of 0.4 m beyond the line (LR). In contrast, not all the material that moved a greater distance was taken into account. The results need to be extrapolated for complete analysis which requires use of a model. The functional principle of this will now be described.

It is presumed that the particles (M) of soil displaced across LR under the effect of implements, can be divided into different classes (M_i) depending on the distance travelled (i). To simplify the expression, i is given in decimeters so that the distances are expressed in whole numbers, this being a prerequisite of the indexed scoring system used in the model. This gives

$$M = \frac{1}{L} \sum_{i=1}^{i=D} M_i \quad (2)$$

where M_i is the total mass of particles carried i dm across LR and D is the maximum distance in decimetres travelled by the gravel.

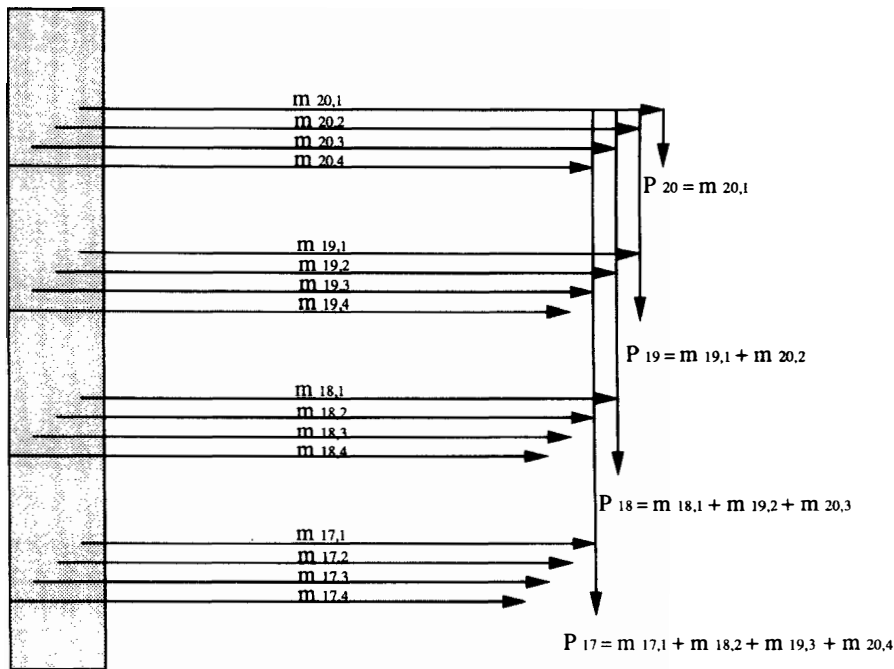
To calculate M , all values of M_i have to be determined between $i=1$ and D . For each value of M_i , the displaced particles are characterised by j , their position in relation to the line LR prior to displacement. This gives

$$M_i = \sum m_{i,j} \quad (3)$$

where $m_{i,j}$ is the mass of soil carried over a distance i and coming from j dm above the line LR (Fig. 2), i and j are expressed in decimeters. For one value of i , j cannot be greater than i . So we have

$$M_i = m_{i,1} + m_{i,2} + m_{i,3} + \dots + m_{i,i} = \sum_{j=1}^{j=i} m_{i,j} \quad (4)$$

It is assumed that soil displacement down a constant slope obeys a steady state (i.e. the mass of soil displaced over distance i is identical at any point on the slope irrespective of its position). This means that whatever the value of j , and for a fixed value of i , $m_{i,j}$ is a



- : 1
- P_i : 2
- m_{ij} : 3

Fig. 2. Diagrammatic representation of use of the model in downhill ploughing: 1, trench; 2, soil weight equivalent taken at i dm from LR; 3, soil weight equivalent carried over distance i and coming from j dm above the line LR.

constant. All the terms in the summation in Eq. (4) are therefore equal and this gives

$$M_i = i m_i \tag{5}$$

Use of this model in our data analysis is illustrated by Fig. 2, taking the case of downhill ploughing in which $D = 20$ dm. In this case at a position 20 dm downhill from the trench it is presumed that all gravel taken from this site (P_{20}) comes from the first decimeter inside the trench, represented by $P_{20} = m_{20,1}$. Sample P_{19} is taken 1 dm nearer to the trench and contains gravel from the first decimeter within the trench which has been displaced over 19 dm ($m_{19,1}$) plus gravel from the second decimeter displaced over 20 dm ($m_{20,2}$), (i.e. $P_{19} = m_{19,1} + m_{20,2}$). If we have a steady state situation this implies that $m_{20,1} = m_{20,2}$. Finally, $P_{20} - P_{19}$, gives the value $m_{19,1}$.

Thus, if one stands at a distance i from the trench, the gravel taken at this position (P_i) consists of gravel from the first decimeter within the trench which has been displaced over i dm ($m_{i,1}$) plus gravel from the second decimeter within the trench which has been displaced over $i + 1$ dm ($m_{i+1,2}$), etc., giving

$$P_i = m_{i,1} + (m_{i+1,2}) + (m_{i+2,3}) + (m_{i+3,4}) \tag{6}$$

Table 2

Estimation of downward soil displacement due to ploughing^a and comparison with rain-induced soil erosion

Slope length (m)	Soil displaced (kg m ⁻²)
<i>After ploughing</i>	
100	1.62
250	0.65
500	0.32
<i>Estimates of soil erosion by rainfall</i>	
Roose and Cavalie (1988)	0.01–0.25
Rouaud (1987)	0.04–0.17
Etchanchu (1988)	0.02

^aTotal amount of soil displaced after one downhill ploughing and one uphill ploughing on a slope of 18% in a 1-m-wide plot.

Calculation of all these equations from $i=1$ to $i=D-3$ and assuming that $m_{i,1} = m_{i,2} = m_{i,3} = m_{i,4}$, produces a system of D equations with D unknowns. By resolving this system, all the m_i terms are determined and thence all the M_i classes and finally the total M .

Resolution of the system is without difficulty in the case of downhill ploughing and gives the sum M_d as 306.8 kg (S_{we}). In the case of uphill ploughing, in contrast, the curve shown in Fig. 1(b) had to be slightly smoothed to solve the equations and determine the sum which was 144.6 kg (S_{we}). Finally, the effect of one single uphill ploughing and one single downhill ploughing is the difference $M_d - M_m$, that is 162.2 kg (S_{we}).

The results in Table 1 show that the downward displacement of soil towards the base of the slope as a result of downhill ploughing is not compensated for by uphill ploughing. The mathematical model produces a result that is more than twice that obtained without extrapolation.

4. Discussion

We compared our results with measurements of rain-induced soil erosion. For this our results had to be expressed in the same way as those of other authors (i.e. in tonnes of soil displaced per hectare, or in kilograms per square metre). The plot that we studied was situated along the greatest slope, as is most frequently encountered in the region. Under such conditions, the amount of soil displaced down a hillside, parallel to the line of slope, with constant slope, is independent of the length of the hillside and only dependent on plot width. However, the mass of soil displaced by ploughing, related to the surface unit ploughed, is inversely proportional to plot length. Some examples of calculations showing values of 0.32–1.62 kg m⁻² are given in Table 2. These results are compared with different measurements of water-induced erosion (Table 2) which were obtained as follows.

First, on the same plot as our trial, Roose and Cavalie (1988) measured sheet erosion, brought about by a sheet or film of water produced with a rain simulator. They found that

the rainfall which has only occurred once in the last 10 years has an intensity of 40 mm h^{-1} and produced scarcely visible effects on the landscape ($0.01\text{--}0.25 \text{ kg m}^{-2}$) compared with our results.

Second, gully erosion in plots in which the slope varied from 3 to 25% was studied by Rouaud (1987). Rills had been produced during spring storms by rainfall intensities of $4\text{--}10 \text{ mm h}^{-1}$ which were average for the region. Their erosive effect was quantified by careful measurement of the volumes hollowed out down the slopes and of the materials accumulated at the bottom of each channel. On the steep slopes, the rills were anastomosed and had excavated the soil to depths of 1.4–5.2 cm. On the gentler slopes, the furrows were rectilinear, covering a smaller surface, but cutting deeper (i.e. 10–14 cm). It should also be noted that in this experiment only a very small amount of the eroded material (i.e. between 11 and 29%) was redeposited at the base of the plot, the remainder being removed from the watershed by surface water. Such run-off produced less total damage ($0.04\text{--}0.17 \text{ kg m}^{-2}$) than ploughing.

Finally, Etchanchu (1988) calculated the overall erosion produced by river action on a watershed. Even when the relationship established by Robinson (1977) was taken into account the calculated erosion (0.02 kg m^{-2}) was very slight.

5. Conclusions

In this experiment ploughing up and down a slope had a very marked erosive effect on a gravel-filled trench. Extrapolation of the results to soil only provided an approximate estimate of the effect of ploughing on downward soil displacement. In addition, certain farmers only plough downhill and not always under good soil moisture conditions. This results in considerable soil displacement towards the bottom of the hillside.

In the long term, mechanical erosion produced by implements has a preponderant impact on surface relief in this landscape, especially on levelling and soil distribution. The displaced materials remain on the slope but extensive surface areas may be deeply scoured. Revel and Rouaud (1985) showed that in the Vermeil watershed (692 ha), 58% of the soil surface was removed to a depth of 1.08 m and that a thickness of 1.47 m of soil was accumulated over only 37% of the surface. This indicates an intense modification of the watershed.

In the region under study, other authors measured the impact of water erosion. The results are variable but the greatest value (0.25 kg m^{-2}) was found after a rainfall event 10 years ago which was still less than the amount of soil eroded by ploughing, even in the most favourable case of a very long plot (0.32 kg m^{-2}). In addition, this latter result was an annual one and did not take other cultivation practices (disc ploughing, harrowing, etc.) into account.

Thus, in this area, ploughing has a greater impact on downward soil displacement than water erosion. In the context of management practices aimed at soil protection, any conservation methods must provide solutions to limit this phenomenon: minimal soil tillage or even zero tillage, high uphill speed, reduced downhill speed, different shaped implements.

New experiments are underway which should provide a better understanding of the impact of cultivation techniques on soil erosion, notably by indicating the role of different para-

meters such as the degree and form of the slope as well as the type of implements used and their velocity.

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