Enrichissement en carbone organique dans les sédiments érodés sous des pluies naturelles ou simulées

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Résumé

La planification de la conservation des sols et des eaux, en vue de lutter contre l'érosion du sol et des nutritifs, nécessite une bonne compréhension des processus et une estimation des paramètres qui y sont liés. Des techniques de conservation, appliquées au niveau d'un champ individuel, encouragent l'estimation des paramètres à ce même niveau mais aussi au niveau d'une pente courte (échelle micro-parcelle).
On le l'a démontré lors des essais au laboratoire et sur le terrain sous pluies naturelles et artificielles en vue de déterminer le transport des sédiments et du carbone organique.

Les sols limoneux (du type 'loess') de la Belgique et de la Chine ont été étudiés. Les résultats des essais sous pluies simulées au laboratoire avec un sol sur loess de Chine indique que le transport sélectif des particules du sol et du carbone organique est limité, mais que les particules grossières sont très sensibles au splash. Les résultats des essais sous pluies artificielles sur des parcelles sur le terrain de la station expérimentale 'Dryland Farming' près de Luoyang (Chine) démontrent qu'au début de l'essai les sédiments transportés sont enrichis en particules fines, mais que cet apport diminue au cours de la pluie.
Le ruissellement venant de parcelles couvertes d'un mulch de paille sous pluies naturelles, révèle un apport augmenté en nutritifs comparé à celui venant des parcelles nues sous pluies simulées. Des essais sous pluies simulées et avec une rigole artificielle au laboratoire, en utilisant un sol limoneux de la Belgique (Maarkedal), indiquent que l'apport en carbone organique avec les sédiments érodés ne se manifeste que avec des débits faibles. D'un autre côté la sélectivité des sédiments, résultant d'un dépôt, est important. Dans ce cas, l'impact et le résultat des mesures de lutte contre l'érosion des nutritifs et des polluants, comme par exemple avec des bandes enherbées, sont plus faibles que l'influence qu'on pouvait attendre. On peut observer un dépôt du matériel érodé juste devant ces bandes, avec un apport sélectif en particules argileuses du matériel en suspension. Ces particules fines transportent sélectivement les nutriments et le carbone organique.

Les résultats des essais au laboratoire et sur des parcelles confirment la sélectivité du transport en matière organique, résultat d'un dépôt de sédiments dans les bandes enherbées. Une augmentation du taux de carbone organique du sol a été observée dans les sédiments en suspension à la sortie d'un petit bassin versant (Maarkedal, Belgique). Un dépôt de sédiments dans les parcelles du bassin versant pourrait jouer un rôle important dans le processus de l'enrichissement de carbone organique.

Mots clés: Belgique, Chine, loess, pluie simulée, pluie naturelle, parcelle d'érosion, transport sélectif, déposition, enrichissement.

ENRICHMENT OF ORGANIC CARBON IN ERODED SEDIMENT UNDER NATURAL AND ARTIFICIAL RAIN

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Abstract

Conservation planning for controlling soil and nutrient erosion requires the understanding of the processes involved and the assessment of parameters governing those processes. As conservation techniques will be mainly applied on individual fields, assessment of parameters on a field level or even at a 'point' scale (short slopes) is encouraged. Examples are given of small laboratory (point scale) and field plot experiments with artificial and natural rain in order to determine transport of sediment and organic carbon. The soils involved are loess derived soils in Belgium and in China.

The results of the laboratory rainfall simulation experiments on a loess soil of China indicate that the selective transport of soil particles and organic carbon is limited. The results of the rainfall simulations on the field plots at the Dryland Farming experimental station near Luoyang show that at the beginning of the tests the eroded sediment is enriched in small particles, but this enrichment decreases as the rainfall simulation continues. Nutrient analyses of the runoff from the field plots under natural rain result in higher enrichment ratios compared to the field rainfall simulations, which is possibly caused by the straw mulch on the field plot surface.

Laboratory rainfall and flume experiments, in which a silt loam soil (Maarkedal, Belgium) was used, indicate that enrichment of organic carbon in the eroded sediment only occurs at very low sediment discharges. On the other hand, the selectivity in sediment transport caused by deposition is more important. In this way, the impact of erosion control measures like grass strips on the reduction of pollutants and nutrients may be less than expected. Grass strips cause deposition of sediment on the field, resulting in an enrichment of clay-sized particles in the suspended sediment. Together with these small particles nutrients and organic carbon are transported. Experimental results in the laboratory and field plots confirm this selectivity in organic carbon transport caused by deposition of sediment in grass strips.

High organic carbon contents were also found in suspended sediment at the outlet of a small watershed (Maarkedal, Belgium). Deposition of sediment within the watershed is possibly the most important sediment enrichment process.

Keywords : China, Belgium, Organic carbon, Selective erosion, Runoff, Deposition, Enrichment ratio, Rainfall simulation

1. Introduction

It is well known that the soil erodibility, and hence the loss of soil from a sloped field caused by runoff, is strongly affected by the soil organic carbon content. The loss of soil from a land surface also depends on the vegetation, which protects the soil surface from the impact of raindrops (above ground organic matter) and ameliorates the (physical and chemical) soil conditions (below ground organic matter). Organic matter is one of the main agents binding soil particles into aggregates and therefore has an important effect on the soil structure. Soil aggregates, composed of primary particles and binding agents, are the basic units of the structure of a soil.

The main organic agents of soil stabilization include the products of decomposition of plant, animal and microbial remains, the micro-organisms themselves, and the products of microbial synthesis. Various inorganic cementing agents (e.g. iron oxides) provide stabilization in certain soils, but in the majority of agricultural soils, organic binding agents are of the greatest importance.

For areas that have suffered severely from erosion, re-vegetation is important, enabling carbon sequestration to restore the eroded land. The traditional way to increase organic matter in cultivated areas is to add raw organic materials like manure, compost or plant materials incorporated as green manure. However, the effect of incorporating green manure only lasts for a short period. Perhaps the most valuable approach to maintain soil organic matter and to protect the soil against erosion is to provide a surface mulch.

Erosion by runoff causes loss of topsoil, which contains a lot of organic matter. Therefore, soil erosion decreases the chemical and physical soil fertility. Depending on the soil type, land use and erosion process, a preferential transport of clay-sized particles can occur. Suspended clay-sized sediment particles in the runoff water can contain 4 times more organic carbon compared to the original soil (Sharpley, 1985; Weigand et al., 1998).

This study focuses on the preferential transport of organic carbon (OC) due to erosion and deposition of sediment. The enrichment of OC in the transported sediment has been studied under natural and artificially simulated rain conditions. The soils involved are loess derived soils from fields in the hilly region of Southern Flanders (Belgium) and from erosion field plots of the Dryland Agricultural Experiment Station (Luoyang) situated in the eastern part of the loess plateau of China.

2. Laboratory experiments on transport of sediment and OC

2.1. Transport of sediment and OC under interrill and rill erosion

Laboratory rainfall simulations were conducted in which soil pans (0.2, 0.6 and 0.9 m long) were filled with loose, air-dried aggregates (< 8 mm). The soil was taken at the experimental fields near Luoyang (Henan Province, China) (Table 1). According to Soil Taxonomy the soil can be classified as an ustochrept. The applied rainfall intensities were 65, 85 and 105 mm h^{-1} during a period of 60 min. Every 10 min runoff and sediment discharge were measured. The OC content of the sediment was determined using the method of Walkley & Black (1934).

Because of the short length of the soil pan, nor rill formation neither deposition was observed. Therefore it was assumed that preferential flow of clay-sized particles would depend on the intensity of the interrill erosion process. However, no effect of erosion intensity, expressed as the unit sediment load, on the enrichment ratio (ER) of OC was observed (Fig. 1).

Table 1. Characteristics of the soils used in the laboratory rainfall simulation experiments

Site	0-2 µm (%)	2-50 µm (%)	50-2000 µm (%)	OC (%)	$CaCO_3$ (%)
Luoyang (China)	15.8	71.0	13.2	0.72	12.1
Maarkedal (Belgium)	15.7	52.3	32.0	0.97	0

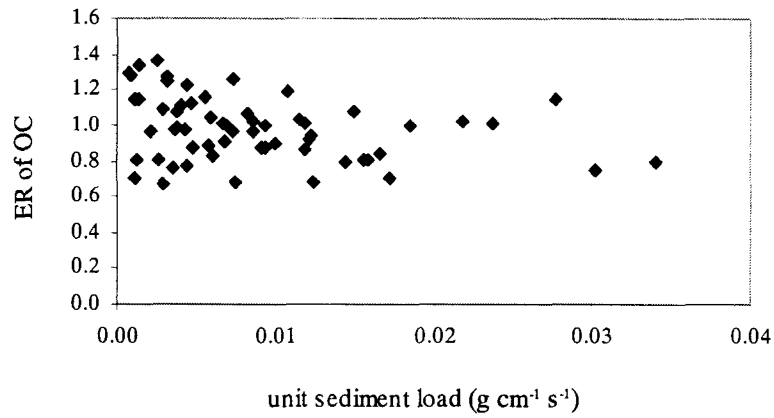

Fig. 1. ER of OC in eroded sediment as a function of unit sediment load (laboratory rainfall simulations on a silt loam soil (Luoyang, China))

Another series of rainfall simulations was conducted on small soil pans (0.55 m long), filled with loose, air-dried aggregates (< 8 mm) of the upper layer (0-5 cm) of a silt loam soil from the experimental fields at Maarkedal (Southern Flanders, Belgium) (Table 1). Rainfall intensities of 20, 40, 70 and 120 mm h^{-1} were applied during a period of 90 min. Every 10 min runoff and sediment discharge were measured and OC in the sediment was determined using the method of Walkley & Black (1934). Small plastic sheets (2x2 cm) were used to obtain cover percentages of 0, 25, 40, 50, 75 and 100 %. The results indicate that the ER of OC in the eroded sediment is higher than 1 at erosion intensities smaller than 0.002 g s^{-1} cm^{-1} (Fig. 2). At higher erosion intensities the ER decreases towards 1. This indicates that selective transport of fine particles only occurred at very low erosion intensities. Moreover, the ER values are much lower than those published by other researchers (Sharpley, 1985; Weigand et al., 1998).

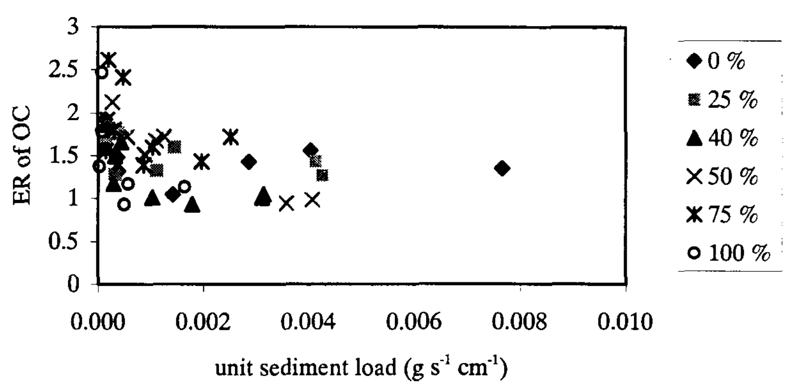

Fig. 2. ER of OC in eroded sediment as a function of unit sediment load (laboratory rainfall simulations on a silt loam soil (Maarkedal, Belgium) with different cover percentages)

In general, it is assumed that interrill erosion is selective and rill erosion is non-selective (Proffitt & Rose, 1991). Rainfall simulations on a preformed V-shaped rill (0.97 m long) were done, using rainfall intensities of 95 and 110 mm h^{-1} and silt loam soil aggregates (< 8 mm) of the experimental fields at Maarkedal (Table 1). Slopes of 10, 20 and 30 % were used. Runoff and sediment discharge were measured every minute. The results showed that the ER values of OC were close to 1, independent of the erosion intensity (Table 2).

Table 2. Average, standard deviation and range of the ER values of OC measured in the eroded sediment during the laboratory rainfall simulations

Site	Erosion experiment	Average	Standard dev.	Min – max
Luoyang (China)	Interrill	0.98	0.18	0.67 – 1.36
Maarkedal (Ghent)	Interrill	1.52	0.40	0.93 – 2.61
Maarkedal (Ghent)	Rill	0.93	0.10	0.80 – 1.07

2.2. Transport of OC and sediment over an area of net deposition

In order to examine the transport of sediment and OC in case net deposition occurs, a flume experiment was conducted. Soil aggregates (< 2 mm) of the upper layer (0-5 cm) of a silt loam soil from the experimental fields at Maarkedal (Table 1) were mixed with water and directed in a non-erodible V-shaped plastic flume (1.6 m long). The runoff discharge was set equal to 0.01 l s^{-1} and slopes of 2, 3, 5, 7, 8 and 10 % were used. Deposition only occurred at slopes less than 10 %. After 10 min the OC content of the eroded sediment was analyzed. The ER of OC as a function of sediment delivery ratio (SDR) is given in Fig. 3. The results indicate that the ER of OC decreases if less material is deposited. If only 20 % of the sediment is deposited (SDR = 0.8), the ER of OC becomes equal to 1.

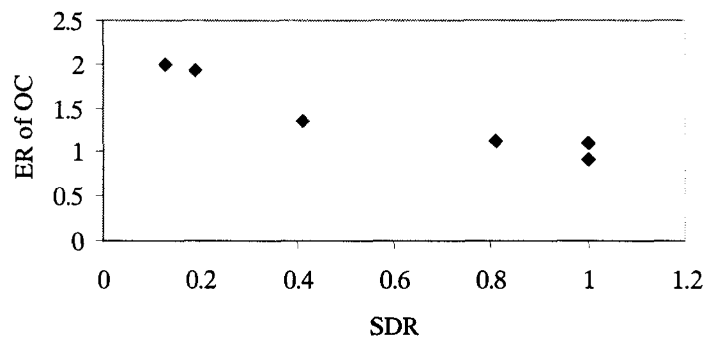

Fig. 3. ER of OC as a function of SDR (flume experiments with a silt loam soil (Maarkedal, Belgium))

Deposition can also be caused by vegetation. In order to examine deposition of sediment and OC by vegetation another flume experiment was done, in which soil aggregates (< 2 mm) of the upper layer (0-5 cm) of a silt loam soil from the experimental fields at Maarkedal were mixed with water and directed in a non-erodible rectangular shaped plastic flume (0.14 m wide and 2 m long). The runoff discharge was set equal to 0.017 l s^{-1} and 0.022 l s^{-1}. Slopes of 5, 10 and 20 % were used. The lower 0.8 m was filled with a grass strip taken at the experimental fields at Maarkedal. After 30 min the OC content of the eroded sediment was analyzed. The ER of OC as a function of SDR is given in Fig. 4. The results of the experiments show a similar trend as in Fig. 3.

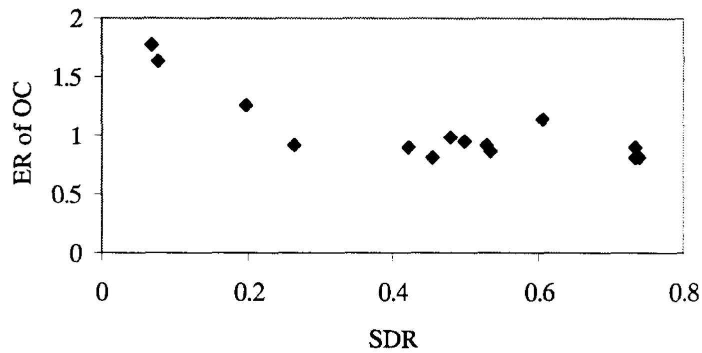

Fig. 4. ER of OC as a function of SDR (grass strip experiments using a silt loam soil (Maarkedal, Belgium))

3. Transport of sediment and OC on a field scale

3.1. Field experiments near Luoyang (China)

Near Luoyang (Henan Province, China) a number of field plots were constructed to measure nutrient and soil losses under different tillage practices. In addition to measurements under natural rainfall conditions, field rainfall simulation tests were carried out on bare soil (Fig. 5). The characteristics of the topsoil are given in Table 3. Samples taken near the field plots were used in the laboratory rainfall simulations (see 2.1.). On the erosion plots, 5 rainfall simulations during one hour were carried out to examine the sediment and nutrient losses at field scale.

Analysis of the OC content and the texture of the eroded sediment showed that the ER changes in time (Fig. 6). In the beginning of the experiment, when erosion intensities are low, higher ER values were found for small particle sizes and OC. As the rainfall simulation continued the ER values decreased towards 1. On the other hand, the ER values of the coarser particle sizes (> 20 μm) showed an opposite trend.

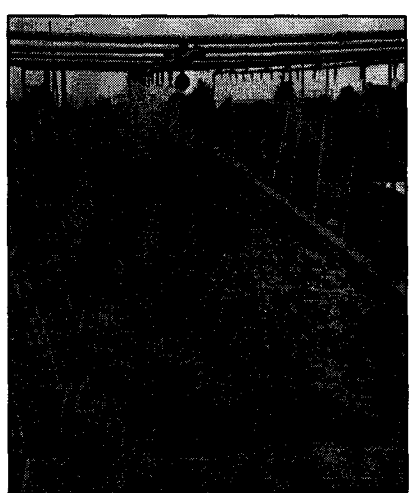

Fig. 5. Field rainfall simulation test on the erosion plots near Luoyang (Henan Province, China)

Table 3. Characteristics of the topsoil of the experimental field plots near Luoyang

Depth	0-2 μm (%)	2-50 μm (%)	50-2000 μm (%)	OC (%)
0-2 cm	14.3	74.8	10.9	0.65
2-30 cm	14.1	74.3	11.6	0.45

The total losses of sediment and OC measured during the rainfall simulations are given in Table 4. The OC content of the eroded sediment varies between 0.64 and 0.79 %. Those values are similar to those measured in the topsoil (Table 3), indicating that enrichment of OC in the eroded sediment is limited.

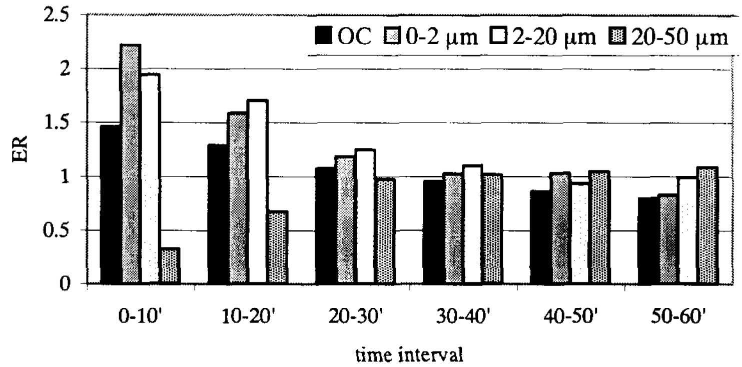

Fig. 6. Change in time of the ER values of OC and texture fractions during a field rainfall simulation on the experimental plots near Luoyang

Table 4. Total losses of soil and OC of the field rainfall simulations on the experimental plots near Luoyang

Simulation	Soil loss (kg m^{-2})	Loss of OC (g m^{-2})
1	16.68	2.12
2	13.22	1.81
3	24.65	3.36
4	14.98	2.35
5	14.32	2.22

In addition to the rainfall simulation tests, runoff from field plots under natural rainfall was measured and analysed. Different tillage practices were applied on these plots: conventional tillage (CT), subsoiling (SS), reduced tillage (RT), no tillage (NT). Because only one rainfall event was monitored, the results are limited and therefore only give an indication of OC and soil losses under the different tillage practices. Measurements are still continuing to provide more validation data. The results of the field measurements show that the soil and OC losses are much lower than those observed during the field rainfall simulations (Table 5), because of lower rainfall intensities. On the other hand the OC content of the eroded sediment varies between 1.41 and 2.39 %, which are higher values than those found in the upper soil layer (Table 3). This can be explained by the surface mulch which acts as a source of OC. Therefore, a more intensive soil sampling (both in space and time) should be carried out in order to have more detailed data about the OC content of the topsoil of these field plots.

Table 5. Total losses of soil and OC after a natural rainfall event (48.4 mm) over a period of 5 days (19 - 24 September 2000)

Plot	Soil loss (g m^{-2})	Loss of OC (g m^{-2})
CT	3.89	0.09
SS	12.86	0.21
RT	4.34	0.06
NT	5.95	0.08

3.2. Field experiments at Maarkedal (Belgium)

At Maarkedal, field experiments were conducted to examine the impact of control measures on sediment and nutrient transport. Part of this research is to study the effect of grass strips on sediment deposition. The experimental field is subdivided in 16 plots, each 100 m long and 1 m wide. Grass strips with different lengths (0, 2, 5 and 10 m) were sown at the lower edge of the plots. Runoff discharge is measured by a tipping bucket system and is sampled flow-proportionally. The sediment in the runoff water is analyzed for texture and OC. During a summer storm, 67 mm rainfall caused a total runoff amount of 23 mm on the reference field (0 m grass strip). On all field plots maize was sown and the crop had a well developed cover. Nevertheless a total soil loss of 0.5 kg m^{-2} was measured on the field without grass strip. On the other fields sediment was deposited in front of and within the grass strips. This resulted in a lower amount of soil loss, but the OC contents of the eroded sediment were higher (Fig. 7). Therefore the ER values of OC increased to 1.9 with increasing grass strip length. Similar results were found for the clay content of the eroded sediment.

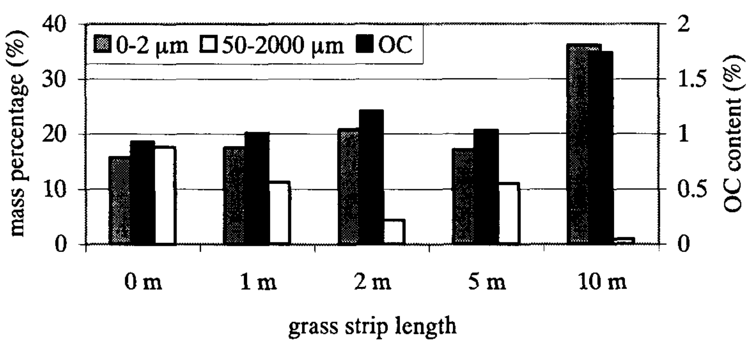

Fig. 7. Clay, sand and OC content of the eroded sediment from field plots with different grass strip lengths (Maarkedal)

3.3. Erosion on a boreal dune at Melden (Belgium)

For a quantitative rill erosion study on this field we refer to Gabriels et al. (1977). During the autumn of 1974 with 47 rain days totaling 213 mm of rainfall, 8 deep rills, spaced about 9 m apart, were observed on the NW exposed slope of a local boreal sand dune formed during the post-glacial Dryas age (11,000 - 8,000 BC). A possible reason for the regular spacing between the rills was attributed to the 9 m width of the manure spraying equipment.

The soil profile is composed of loamy sand with an argillic horizon and a loamy substratum at low depth. The soil upper layer contains 4.1 % clay (0 - 2 µm), 25.2 % silt (2 – 50 µm), 70.7 % sand (> 50 µm) and 1.05 % OC. The slope of the field is 5% from the base till a distance of 100 m upslope where the deep rills originated. The deep rills were surveyed in such a way that a cross-section was measured every 5 m along the rill length. As during rill development also deposition of soil material occurred in the rill, the total erosion was considered as the sum of the rill volume and the deposition in the rill. Hence the erosion from 8 rills on a 1.4 ha field was estimated at 11.5 tons, corresponding to a soil loss of 1.3 mm in 2 months of heavy rainfall (213 mm).

The upper 2 cm soil layer was analyzed at different positions on the field (Table 6)
- initial condition of the soil before rill development (*initial field*)
- sediment deposited at the erosion base (*erosion base*)
- sediment deposited 10 m further downslope of the erosion base on the grassland (*grassland*)

Mainly very fine sand (50-100 μm) and the fine sand fraction (100-200 μm) were deposited on the erosion base; the clay and OC were carried with the runoff water further downslope on the grassland where the water could infiltrate. Therefore, higher clay and OC contents were found in the sediment deposited in the grassland.

Table 6. Granulometric composition (in %) and OC content (in %) of the sediment at different places on the eroded slope (Melden)

	Initial field	Erosion base	Grassland
< 2 μm	4.1	1.4	6.5
2-20 μm	8.8	0.9	5.2
20-50 μm	16.4	11.2	35.4
50-100 μm	34.8	45.1	34.7
100-200 μm	29.7	34.6	15.5
200-500 μm	6.1	6.7	2.6
> 500 μm	0.1	0.1	0.1
OC	1.05	0.15	1.3

3.4. Field experiments at Kemmel (Belgium)

At the lower edge of a 300 m long arable field, grass strips with different lengths (0, 1 and 2 m) were sown. After the harvest of potatoes, the field was left bare during the winter period. In December 1999, a total rainfall amount of 120 mm during a one week period caused severe erosion on the field. At the lower field edge, a lot of the eroded soil was deposited causing the grass strips to be saturated with sediment. Analysis of the sediment deposited in front of the grass strips showed that the deposited material was depleted in fine particles and OC (Table 7). Therefore, the runoff water and suspended particles that finally reached the river might be enriched in clay and OC. Control measures like grass strips, which enforce deposition of eroded material, are effective in reducing sediment transport, but might be less efficient in the reduction of non-point source pollution caused by eroded clay-sized particles and OC.

Table 7. OC content and texture analysis of sediment deposited in front of grass strips, compared to the topsoil of the eroded field (Kemmel)

Location	OC (%)	0-2 μm (%)	2-50μm (%)	50-2000 μm (%)
Topsoil of the eroded field	0.91	13.2	40.9	45.9
Deposition in front of 1 m grass strip	0.32	6.4	36.2	57.4
Deposition in front of 2 m grass strip	0.28	3.7	33.7	62.6

4. Transport of sediment and OC on a watershed scale

During several rainfall events, water samples were collected at the outlet of a small rural watershed (2.7 km^2) at Maarkedal (Belgium). The sediment concentration in the samples was determined and the OC content of the sediment was analyzed using the method of Walkley & Black (1934). The results show a tendency of decreasing OC contents in the sediment with increasing sediment concentrations (Fig. 8). In order to determine the spatial variability of the OC content within the watershed, samples were taken from the topsoil (0-5 cm) at 72 points, of which 53 were situated on arable land. Analysis of the samples showed that the average OC content of the topsoil taken at the arable fields varied between 0.75 % and 5.25 % with an average OC content of 1.34 %. This average value is lower than those observed in the sediment samples (Fig. 8), indicating that enrichment in OC takes place along the runoff pathway, from the place where erosion starts towards the outlet of the watershed. Possibly, the higher ER values of OC are the result of deposition processes that favour the transport of small particles and hence OC. Higher sediment concentrations occur at higher runoff discharges and therefore in conditions with less sediment deposition and even with re-entrainment of deposited material. However, on a catchment scale different sediment transport processes interact, causing erosion at one place and deposition at another. Moreover, there is a lot of spatial variability regarding the OC content of the soil, because of differences in soil texture, land use and management. Therefore the measured sediment and OC concentrations at the outlet of the watershed are the resultant of different factors and processes. In order to indicate the main processes and factors in the transport of OC, also the spatial erosion and deposition pattern within the watershed has to be examined.

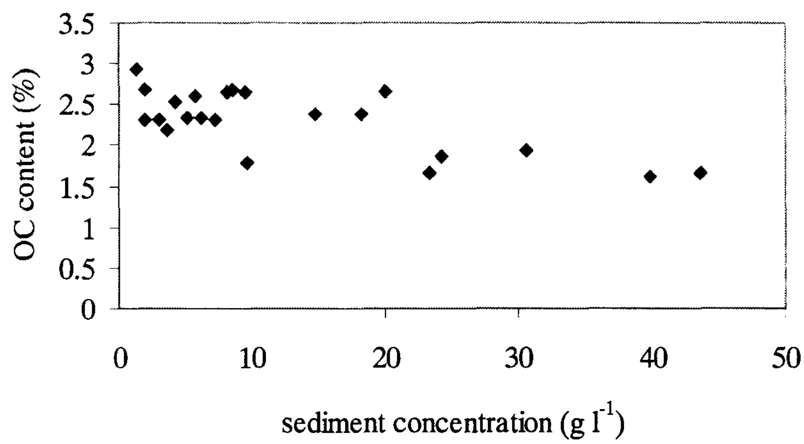

Fig. 8. Sediment concentration versus OC content of the sediment sampled at the outlet of the Mariaborrebeek watershed (Maarkedal)

5. Conclusions

Deposition, interrill and rill erosion processes were simulated in the laboratory, using artificial rainfall in order to study transport of sediment and OC. The results of the experiments showed that enrichment of OC occurs at low erosion intensities. However, the ER values are small. Based on field rainfall simulations similar conclusions could be made. This indicates that the preferential transport of OC caused by erosion is rather limited. Field measurements showed that the OC content of the deposited sediment is low compared to the original soil. Therefore, the selectivity of the deposition process seems to be more important in the enrichment of OC in the eroded sediment that reaches the channels and eventually the watershed outlet. Analyses of samples taken at the watershed outlet indicate an enrichment in OC content of the sediment. However, also the deposition and erosion patterns within the watershed have to be examined to obtain a better understanding of the processes and factors causing preferential transport of OC at a watershed scale.

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