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Developing a magnetic tracer to study soil erosion

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Abstract

Soil erosion is commonly measured as the quantity of sediment leaving a plot or watershed. The techniques for measuring soil erosion patterns and sediment redistribution within plots or watersheds by direct monitoring are very limited. The objective of this study was to develop a direct and non-intrusive tracer method to study the sources, patterns and rates of erosion and deposition of sediments in erosion plots. The magnetic tracer developed in this study consisted of polystyrene plastic beads embedded with a magnetic powder (magnetite). The "magnetized" beads, with a mean weight diameter of 3.2 mm and particle density of about 1.2 g cm^{-3}, were uniformly mixed with soil and tested in the laboratory using simulated rainfall and inflow studies to simulate the interrill and rill components of soil erosion, respectively. In the interrill and rill experiments, the tracer was transported in the same proportion it was initially mixed with the soil. Given this fact, a magnetometer, which measures the soil's magnetic susceptibility, could be used to identify areas of deposition or detachment. The magnetic susceptibility would be increased or reduced depending on whether deposition or detachment occurs. To simulate detachment and deposition, a magnetometer was tested for different tracer concentrations and different thickness of soil containing the tracer. The magnetometer promises to be a sensitive, accurate, and useful tool to study the spatial variation of soil erosion when magnetic tracers are used. Published by Elsevier Science B.V.

Keywords: Soil erosion; Interrill erosion; Rill erosion; Magnetic tracer; Sediment

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1. Introduction

Most of the methods now used to measure soil erosion provide information on the average rates of delivery of sediment from designated study areas, but do not provide information on the origin of the sediment leaving the area, nor about how sediments are re-distributed within landscapes. Information on the temporal and spatial distribution of soil erosion is required to better understand the process of soil erosion and to evaluate physically based hillslope or watershed scale erosion models (Morgan et al., 1998; Nearing et al., 1989; Flanagan and Nearing, 1995) which now have the capacity to provide estimates for erosional distributions.

The analysis of ^{137}Cs within the landscape has been used a method for assessing long-term soil erosion and net deposition at various spatial scales. Fallout ^{137}Cs measurements have been used in research of soil erosion by water in a wide range of environments and in many different areas of the world over the past 20 years (Walling and He, 1999). Cesium-137 distributions are normally used to represent an erosional average relating to the past 30 years (Walling and Quine, 1991; Garcia-Oliva et al., 1995). In addition, the existing calibration procedures commonly used for deriving quantitative estimates of soil redistribution rates involve several limitations and uncertainties (Walling and He, 1999). Other limitations, including the sampling and detection time for measuring ^{137}Cs content, as well as scale limitations, have been mentioned by Walling and Quine (1991).

Another sediment tracer technique which is showing promise is the use of rare earth elements (Junliang et al., 1994). Rare earth elements absorb quickly to soil and sediment, are found in very naturally in only small concentrations in soils, and are non-toxic. A major limitation to this technique, however, is the high cost of sample analysis.

The objective of this study was to develop a new magnetic tracer technique for measuring the movement of sediment caused by water erosion. We set out to develop a synthetically constructed, magnetic material which moves with the soil during erosion events, and which can be measured with a magnetometer before and after erosion events. This technique has several potential advantages over current sediment tracer techniques. It requires no destructive sampling in order for measurements to be taken. Magnetometer readings are taken from the soil surface in a completely non-destructive manner. Once the initial equipment is obtained, the technique is extremely simple, quick, and inexpensive. This paper deals with the basic preliminary studies of the construction of the synthetic beads and their basic response to rill and interrill erosion processes.

2. Materials and methods

2.1. Manufacturing process of magnetic beads

The essential materials that are required to manufacture the magnetic tracers are plastic beads and magnetic powder. These two materials are commercially available. For

Table 1
Properties of the magnetite powder used to manufacture magnetic plastic beads

Property	
Screen size	
% Passing 100 mesh + 200 mesh	1.0
% Passing 200 mesh + 325 mesh	9.0
% Passing 325 mesh	90.0
Apparent bulk density (lb/ft^3)	150.0
Specific gravity	5.1
% Magnetics (Davis Tube)	96.0
Fe total	71.0
Fe (magnetic)	68.7

Source of data: Pea Ridge Iron Ore. http://www.pearidgeiron.com).

this study, three different types of beads and three different magnetic powders were initially examined. The plastic beads tested were different in shape and chemical composition. The first type had a round shape and was composed of polystyrene. The other two had oval and elongated forms and were composed of acetate. The three magnetic powders initially examined were M-25 Iron Oxide (Fe^3O^4), H-25 Iron Oxide (Fe^2O^3), and PRIMAG (Fe^3O^4) or magnetite (Pea Ridge Iron Ore, Sullivan, MO, USA). Finally, based on the magnetic properties and the quality of magnetized beads, PRIMAG (Fe^3O^4) was selected as the magnetic powder to be used in the making process of magnetic tracers (Table 1). The manufacturing process consisted of mixing the magnetite powder with the plastic beads in an approximate 7:1 ratio by volume and putting them in the oven at 200°C for approximately 1 h to reach the melting point of the plastics. Some extra plastic beads were placed on top to observe when melting occurred. Then, the mix was taken out of the oven, carefully stirred and cooled before screening it through a sieve to separate the magnetite powder from the “magnetized” beads. A picture of a round “magnetized” plastic bead showing how the magnetic powder is embedded after the manufacturing process is shown in Fig. 1. It was easier to make the round magnetic beads than oval and elongated. This was in part due to the chemical composition of these two plastic beads. The oval and elongated beads expelled chemical gases that are harmful if inhaled. All three types of beads were mixed with soil aggregates and tested in the laboratory.

2.2. Physical characteristics of the magnetic beads

2.2.1. Shape and size

A picture of the three types of beads, in their raw and magnetized form, is shown in Fig. 2. The purpose of testing different shapes of beads was to determine the effect of different shapes on the amount of magnetic beads detached by the interrill and rill processes and to define which shape was the most appropriate for the studied soil. In general, 97.74% of round beads had sizes between 2 and 4 mm. The mean weight diameter (MWD) of the round beads was 3.2 mm. The elongated beads were more homogeneous; with size varying only from 2 to 3 mm and an average of 2.50 mm. Oval

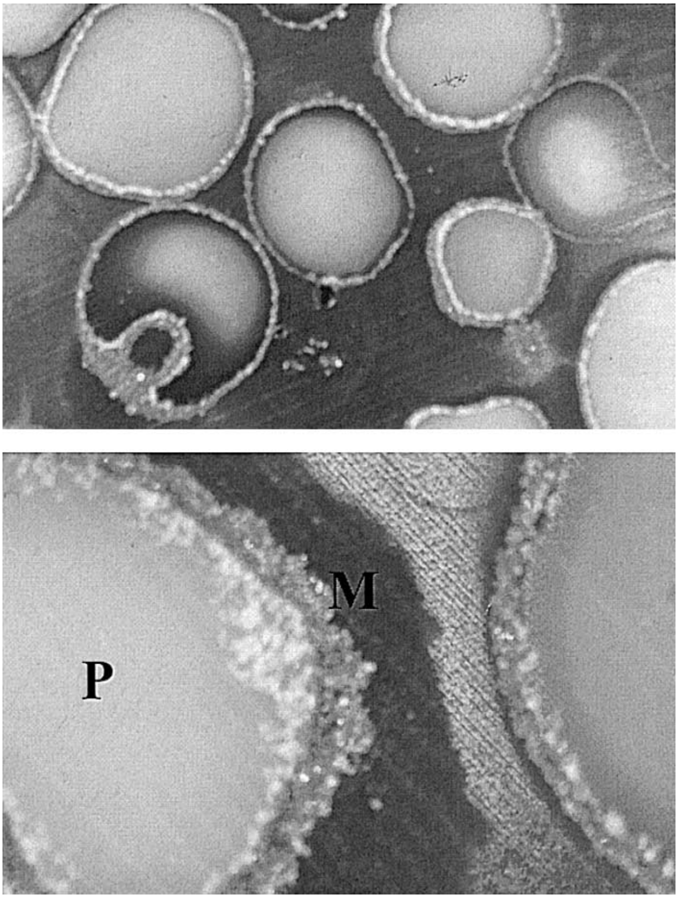

Fig. 1. Thin section view of the round plastic beads (P) with coating of magnetite (M).

beads were also homogeneous and varied in size from 2 to 4 mm, with a mean weight diameter of 2.54 mm.

2.2.2. Density of beads

Particle density of magnetized beads, as determined with the picnometer method (Blake and Hartge, 1986), varied from 1.21 g/cm^3 for the round beads to 1.47 g/cm^3 for the elongated and 1.53 g/cm^3 for the oval beads.

2.3. The soil

The soil used in this experiment is a Cincinnati silt loam and it is classified as a: fine-silty, mixed, mesic, typic Fragiudalf from Sullivan County, IN. Soils belonging to this series are located in areas with slopes between 5% and 10% and are highly susceptible to soil erosion. Soil samples were taken from an undisturbed area. The soil

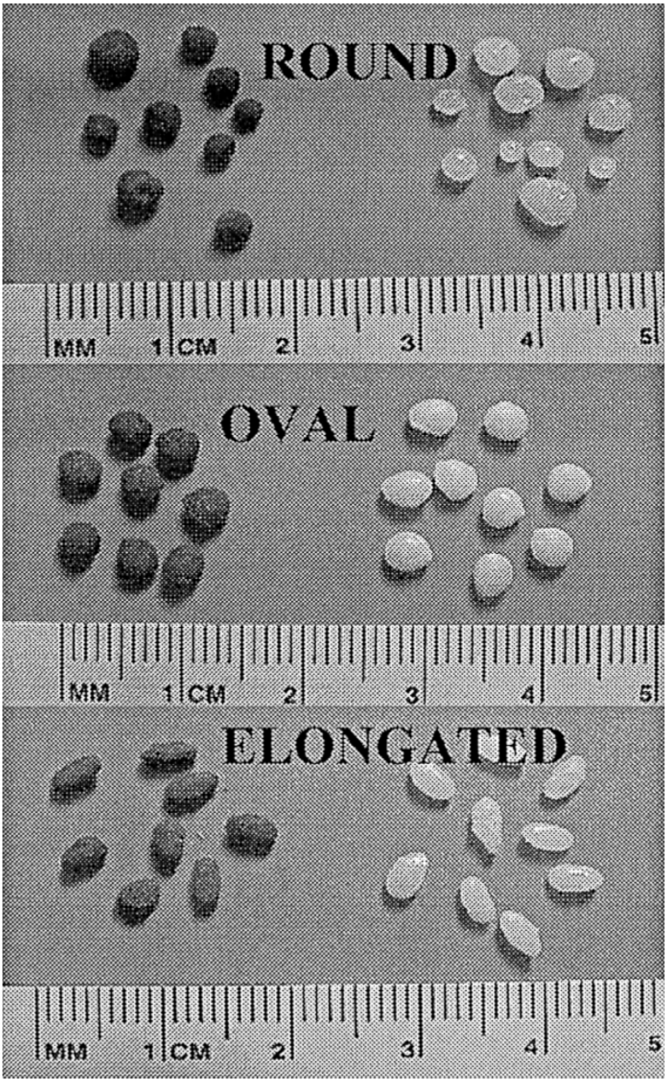

Fig. 2. Round, oval, and elongated plastic beads: coated with magnetite (left) and uncoated (right).

has an average of 14.5% of clay, 7.5% sand and 78.0% of silt. The soil was formed in loess deposits as reflected by the considerable content of silt. The mean weight diameter of dry aggregates sieved through an 8-mm mesh was 2.0 mm.

2.4. Testing of the soil erosion process

2.4.1. Testing of magnetic beads in the interrill area

For this study, soil samples were collected at field moisture. After air-drying, the soil was gently ground using a wood roller and then gently passed through an 8-mm sieve.

The sieved soil was mixed homogeneously with the magnetic beads in the desired proportions. Then, the mix was packed to depth of 3 cm to a density of 1.3 mg m^{-3}, similar to the natural bulk density of this soil in the field, in a soil erosion pan 32 cm wide, 45 cm long, 20 cm deep and with supporters 45 cm high. The pan had a 14-cm bottom layer of gravel with a diameter of > 4.75 mm, and a 3-cm intermediate layer of silica sand to control moisture. Once the soil was packed, it was prewetted by capillary rise for about 2 h with deionized water in a horizontal position. After saturation, the pan was set at 10% slope and allowed to drain for about 30 min. A 5-cm tension, measured at the center of the soil erosion pan, was set and kept during the drainage and the simulated rainfall events. Simulated rainfall events consisted of a constant intensity rainfall applied for 2 h at a target rate of 75 mm h^{-1} with the actual rate was measured. Rain was applied using a programmable rain simulator with four 80–100 Veejet nozzles (Niebling et al., 1981) located 3 m above the center of each erosion pan. A constant pressure of 6 psi was maintained at each nozzle. In order to simulate natural rain, deionized water with electrical conductivity (EC) less than 18 μS cm^{-1} was used as rainwater. Runoff and sediments were sampled at the bottom edge of the pan using wide-mouth polyethylene bottles. Samples were taken every 5 min. The magnetic beads were separated from the soil with a magnet and both the soil and tracer detachment quantified. Four tracer concentrations were evaluated in the interrill area for each type of bead. The concentrations by weight were 2.5%, 5%, 10% and 15%, which corresponded to equivalent soil/tracer ratios of 40:1, 20:1, 10:1 and 6.67:1, respectively.

2.4.2. Testing of magnetic beads in the rill area

The purpose of this test was to evaluate the detachment of the magnetic tracers in the rill area. A 1-m long and 10-cm wide rill was packed with a mix of sieved soil and magnetic beads with a 5% concentration by weight. The soil was then saturated and drained for 30 min before applying increasing amounts of water (inflow rates) at the upper end of the rill with the rill slope set at 10%. The inflow rates applied varied from about 1.5–8 l/min. Three samples were collected for each inflow rate to measure soil and tracer detachment.

2.5. Testing of the magnetometer

The magnetometer selected for testing was the *MS2* Magnetic Susceptibility System (Bartington Instruments, 1997, Oxford, England). The *MS2* System measures the magnetic susceptibility of materials. Commonly measured materials include rocks, soils, river sediments, marine sediments, atmospheric dusts and building materials. Magnetic susceptibility is a measure of the magnitude of how ’magnetic’ a sample is. The system used consists of a meter, a probe handle and a range of interchangeable sensors. The sensors selected for testing were a search loop (*MS2*D) and a small tip probe (*MS2*F). The *MS2*D search loop is a field probe, 185mm in diameter, designed to make surface measurements of soils, rocks, stream channels, etc. The *MS2*F field is used to measure small scale ($\sim 10^{-2}$ m) spatial variations in the magnetic susceptibility of geological exposures, soil pits and individual stones and clasts. Both probes are used in conjunction with the *MS2* probe handle and display unit. A picture of the magnetometer and its components is shown in Fig. 3.

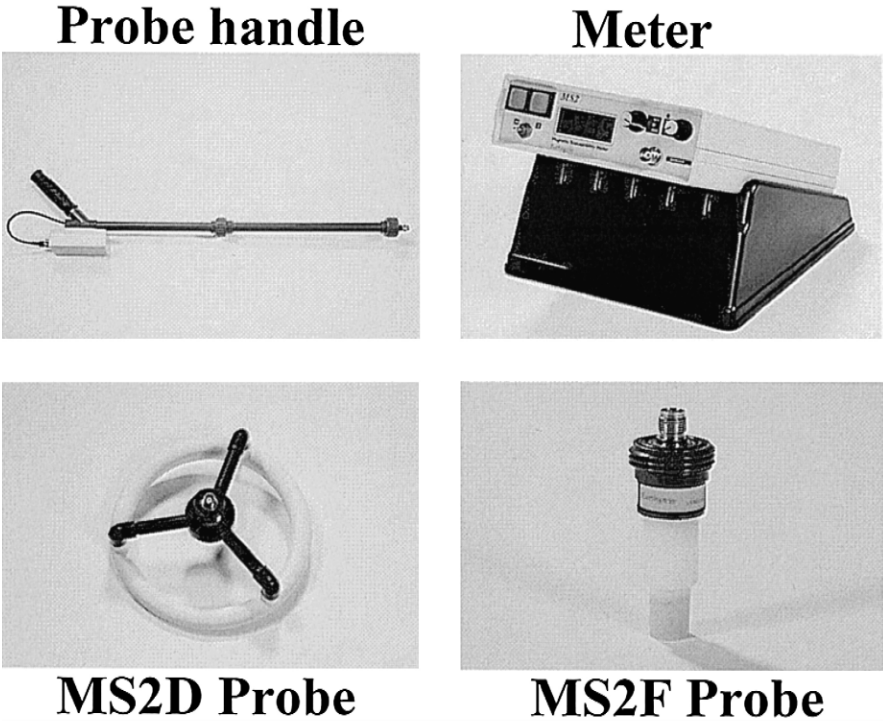

Fig. 3. Magnetometer equipment and probes.

Susceptibility measurements were made in soil samples with different magnetic tracer concentrations, ranging from 1% to 15% by weight. Larger concentrations would be of limited practical application due to the amounts of tracer required to cover a given area. For a selected concentration of 5% of beads in the soil, the magnetic susceptibility was measured in samples with different thickness, ranging from 0 to 12 cm. The measurements provided information on how deep the magnetic layer should be to accurately detect soil movement due to soil erosion and deposition.

3. Results and discussion

3.1. Testing in the interrill area

Soil and tracer detachment from the interrill area, where raindrop splash and shallow overland flow are the dominant processes moving particles, are shown in Fig. 4 for the round magnetic beads. The results indicated that for a soil/tracer mix ratio of 40:1 (2.5%), the tracer was preferentially retained in the interrill area. Sediments leaving this area had a tracer concentration of 0.7% at steady state conditions, which corresponds to

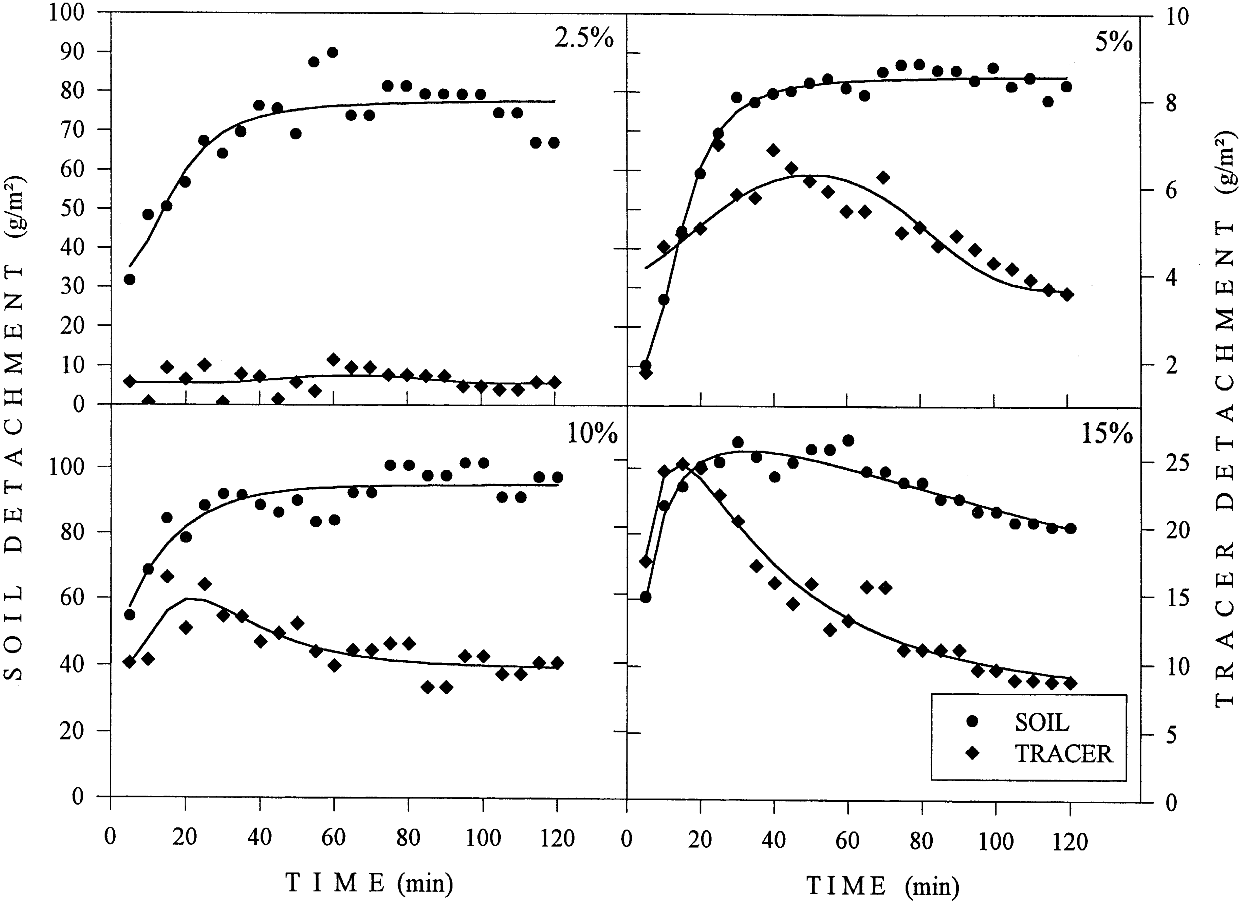

Fig. 4. Soil and tracer detachment from the interrill area, where raindrop splash and shallow overland flow are the dominant moving processes of particles, for the round magnetic beads at 2.5%, 5%, 10%, and 15% concentrations.

soil/tracer ratio of 140:1. For a tracer concentration of 5%, which is a soil/tracer ratio of 20:1, at steady state conditions the sediments leaving the interrill area have a tracer concentration between 4.3% and 4.5% (soil/tracer ratio of about 22:1). This ratio was acceptable and representative of the original mix and indicated that soil and tracer moved in the same proportion out of the interrill area. A soil/tracer ratio of 10:1 (10%) consistently yielded sediments out of the interrill area with a tracer concentration of 10.2% at steady state conditions. This nearly perfect 9.8:1 soil/tracer ratio was representative of the original ratio in the interrill area and was considered as good as the 20:1 ratio to be used in soil erosion studies involving this type of magnetic tracers.

The greater concentration of tracer in the interrill area modified the magnitude of the soil erosion detachment with time, as indicated in Fig. 4 for the 15% concentration. At this high concentration, the soil detachment decreased due to the protection of the magnetic beads on the soil surface against the raindrop impact. This dissipation of energy is the result of a greater soil surface covered with magnetic beads. The final soil/tracer ratio of sediments out of the interrill area had a value of 9:1 or 11% tracer concentration. A soil/tracer ratio of 6.67:1 was expected. The soil detachment for 2.5%, 5% and 10% tracer concentration, reached a plateau under steady state conditions, while with 15% soil detachment clearly decreased with time after reaching a maximum. Similar results were obtained with the oval and elongated magnetic tracers. Armoring effects were observed on the soil surface for all the treatments with 15% tracer concentration.

There are some apparent differences in the forms of the detachment vs. time curves for the sediment vs. that of the tracers as shown in Fig. 4, which we cannot explain. While the curves for sediment tend to increase and then stabilize over time, the tracer curves tend to show an initial peak before leveling off to a lesser value over time. This could cause some problems of interpretation when comparing measurements of small to large erosion events using this technique. Further work with variations in the size of the magnetic beads could potentially improve this less than optimal effect.

We conclude from these results that a tracer concentration of 2.5% is too small for the magnetic tracer to be used in soil erosion studies. On the other hand, concentrations greater than 15% will modify the soil erosion detachment by providing additional protection against the raindrop impact. Soil/tracer ratios between 20:1 (5%) and 10:1 (10%) appear to be appropriate for soil erosion studies with this type of magnetic beads.

For a concentration tracer of 5%, equivalent to a soil/tracer ratio of 20:1, the soil and tracer detachment for the three different magnetic beads is presented in Fig. 5. No significant differences were found between the three bead types tested. Sediments obtained from the round bead treatment had a tracer concentration at steady state conditions that ranged from 4.3% to 4.5%. The concentration of magnetic tracer for the oval beads ranged from 4.2% to 4.4%, and the corresponding value for the elongated tracers was 4.3%. Based on the above results, we can conclude that any of the three magnetic beads can be used as tracers in interrill erosion studies. However, it is important to mention that the manufacturing process of oval and elongated beads is more difficult due to their chemical composition. Additionally, the quality of magnetized beads was not as good as that of the round beads, because a complete impregnation with the magnetite powder was not always achieved.

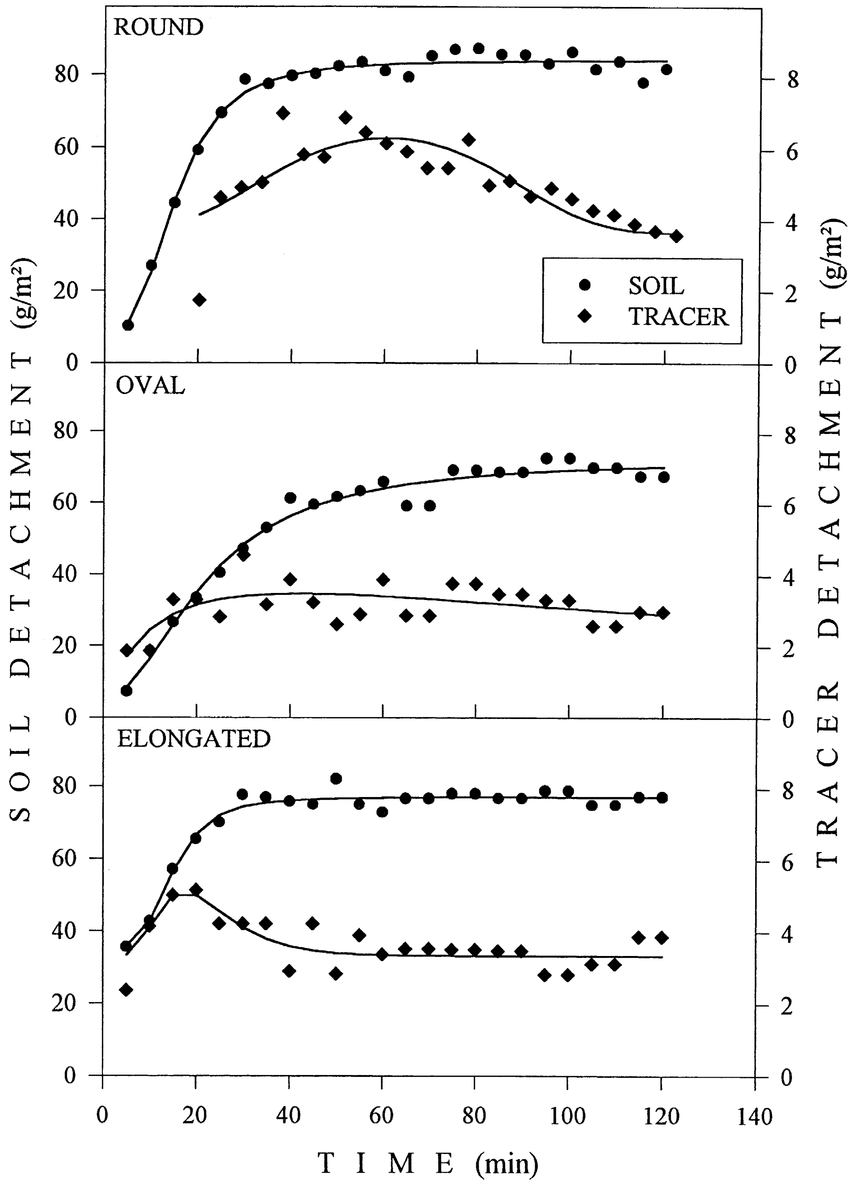

Fig. 5. The soil and tracer detachment from the interrill area for the three different magnetic beads at a 5% tracer concentration.

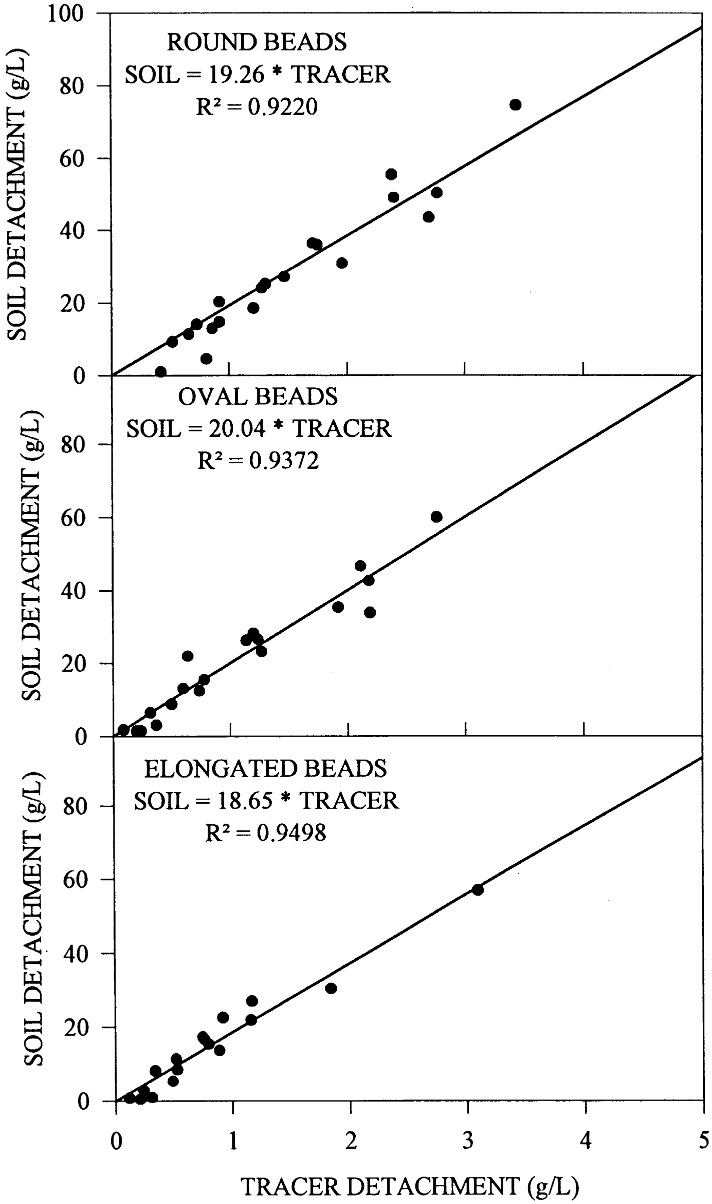

Fig. 6. The soil and tracer detachment in rills for the three types of magnetic beads.

3.2. Testing in the rill area

The soil and tracer detachment in rills for the three types of magnetic beads is shown in Fig. 6. A soil/tracer ratio of 20:1 (5% concentration, wt/wt) was used in the rill erosion experiments. The regression line and corresponding equation is presented for each type of magnetic beads. The slope of the regression gives the soil/tracer ratio of sediments resulting from runoff in the rill. The slope of the regression equation between soil and round magnetic beads detachment was 19.26. This value was very close to the expected value of 20, which is the original soil/tracer ratio in the rill area. The coefficient of determination (R^2) of this regression equation was 0.9220, indicating a consistent relationship between soil and tracer detachment for increasing amounts of runoff.

The value of the slope in the regression equation obtained for the oval beads was 20.04, indicating that the soil and tracer were carried by the runoff in the same ratio as the original concentration. The coefficient of determination in this case was 0.9372, indicating that a high percentage of the variation was explained by the regression equation obtained. The equation obtained for the elongated beads had a slope of 18.65,

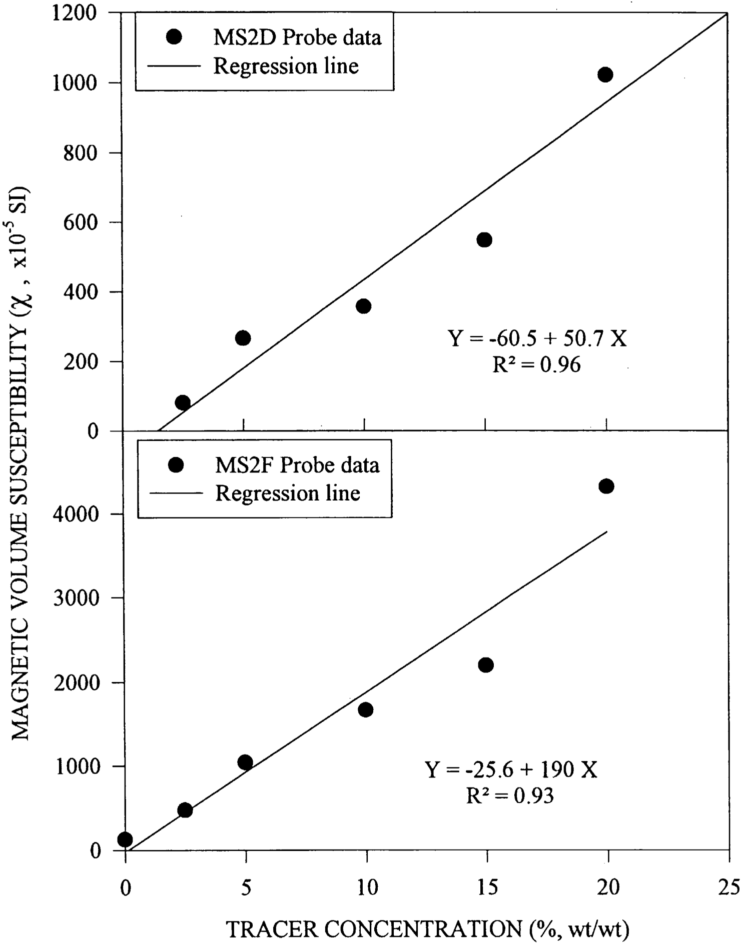

Fig. 7. The volume magnetic susceptibility for different concentrations of magnetic tracer mixed uniformly to a soil depth of 5 cm.

which may also be considered acceptable for an expected value of 20. The three types of beads performed well in the rill erosion experiments. These good results may be explained by the fact that once the flow is concentrated in the rills, the transport capacity of the runoff increases notably and is less selective in transporting the soil aggregates and magnetic beads. In summary, for rill erosion studies, all three magnetized beads can be used reliably.

3.3. Testing of the depth of the magnetic layer and tracer concentration for two probes

An important factor in evaluating the potential of this technique is to understand the response of the magnetometer to varying depths of tracer thickness. In theory, eroded

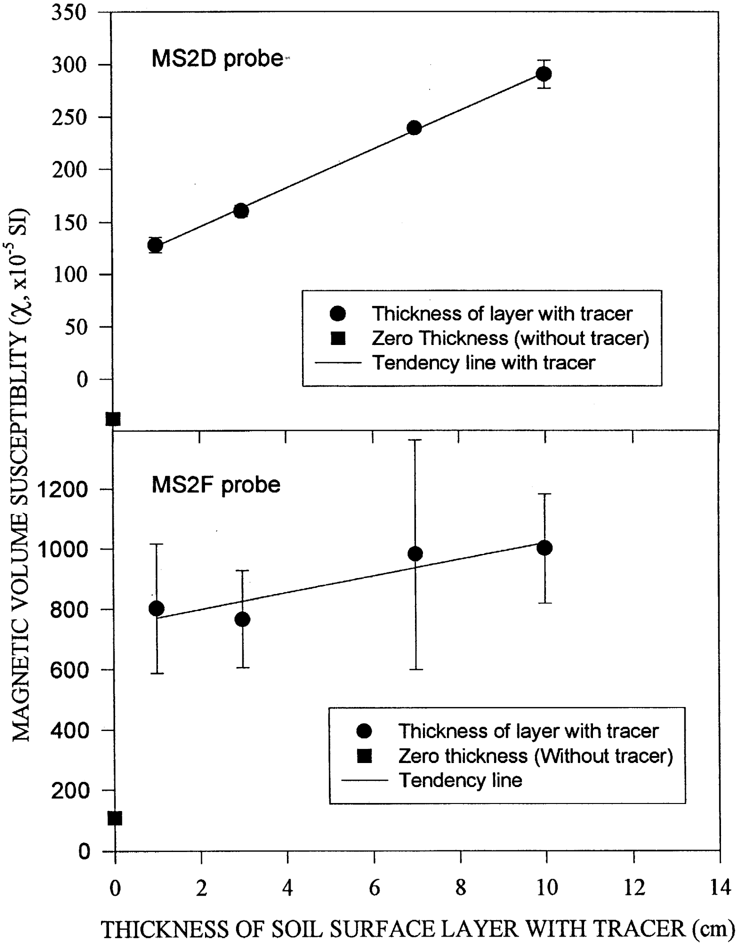

Fig. 8. The measurements of volume magnetic susceptibility as a function of depth of mixing with the soil. The surface thickness of the soil mixed with magnetic beads varying from 0 to 10 cm. A constant tracer concentration of 5% was used.

areas should have a thinner remaining tracer layer thickness, giving a lesser magnetometer reading, and depositional areas should show a corresponding greater reading. Also, if the magnetometer is responding appropriately, it should show a sensitivity to the concentration of the magnetic beads in the soil.

Results of magnetic susceptibility measurements for different concentrations of magnetic tracer to a uniform depth of 5 cm are given in Fig. 7 for the MS2D loop probe and the MS2F probe. Both probes indicated an increase in magnetic susceptibility as the concentration of magnetic beads in the soils increased.

Results of the measurements as a function of the thickness of the magnetic layer are shown in Fig. 8. A constant tracer concentration of 5% was used in this test. The measurements made with the MS2F probe showed a great amount of variability in the measured magnetic susceptibility values for this test. The problem with the MS2F probe (Fig. 3) is that it measures magnetic susceptibility over a very small volume of soil, and will indicate a very high reading of susceptibility if a single magnetic bead happens to be located against the probe during the measurement. The MS2D loop probe, on the other hand, integrates the magnetic susceptibility over a much larger sol volume, and showed a steady change in the magnetic reading as a function of magnetic layer thickness.

4. Conclusions

The use of round magnetic beads, with similar size and density of natural soil aggregates, made with polystyrene and magnetite powder as tracers to study the soil erosion is recommended based on the feasibility of the manufacturing process and the results obtained in the interrill and rill experiments. Concentrations of tracer ranging from 5% to 10% can be used with reasonable results. Greater concentrations apparently affect the amount of soil detached due to the armoring effect of beads and the subsequent protection against raindrop impact due to the resistance of the beads to break down.

The magnetic tracer developed in this study would be homogeneously mixed with soil in the top 3–5 cm to enhance the soil magnetic properties. A magnetic map of the area of interest can be obtained as original reference by measuring magnetic susceptibilities. After a rainfall event or after a time of interest, the changes in thickness of the magnetized layer over different parts of the hillslope can be detected with the magnetometer. Thicker areas would be areas of accumulation and would have a greater magnetic susceptibility, while areas of detachment would be thinner with lesser magnetic susceptibility values. The original map could then be compared to the actual and the redistribution of soil can be studied.

We found that the appropriate magnetic probe for use in this application was a loop-type probe (MS2D) which integrated over a relatively large volume of soil and showed a clear change of magnetic reading with the thickness of the magnetic layer in the soil.

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