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A field method for soil erosion measurements in agricultural and natural lands

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Abstract: Soil erosion is one of the most important watershed processes in nature, yet quantifying it under field conditions remains a challenge. The lack of soil erosion field data is a major factor hindering our ability to predict soil erosion in a watershed. We present here the development of a simple and sensitive field method that quantifies soil erosion and the resulting particulate nutrient movements in a landscape. The method is based on the principle of the mesh-bag (MB) method that quantifies the redistribution of the eroded soil in a field. The mesh bags allow water and a negligible amount of soil particles to infiltrate the bottom mesh because they are intimately in contact with the bare soil surface. We evaluated the MB method with a runoff plot method and confirmed that soil erosion on a slope assessed by the two methods is significantly and positively correlated. The efficiency of the MB method to assess soil erosion increased with decreased slope or increased plot size. The practical upper limit of the MB method to assess total soil erosion is 15.5 t ha^{-1} (6.3 tn ac^{-1}) in 26 to 47 m^2 (280 to 506 ft^2) plots with 5% to 10% slopes and 6.5 t ha^{-1} (2.6 tn ac^{-1}) in a 35 m^2 (377 ft^2) plot with 25% slope. Mesh-bag sizes, ranging from 10 × 10 to 30 × 30 cm (3.9 × 3.9 to 11.8 × 11.8 in), had no significant effect on the amount of soil erosion assessed. The spatial and temporal patterns of soil erosion and the associated nutrient movement revealed by the MB method may provide valuable insights into the soil erosion processes in agricultural and natural lands.

Key words: agriculture—erosion measurement—mesh-bag method—nutrient movement—runoff plot—soil erosion

Soil erosion is a ubiquitous natural watershed process. Accelerated soil erosion, however, could deplete soil productivity and impair stream water quality of a watershed (Lal 1994). Many methods have been developed for soil erosion assessment over the years, and yet quantifying soil erosion under natural field conditions, especially at a landscape scale, remains a challenge (Hornung 1990; Keim and Schoenholtz 1999; Thomas et al. 1999; Nearing et al. 2000; Trimble and Crosson 2000). For example, volumetric methods, such as erosion pins or stakes, have been widely used despite having some serious uncertainties in soil erosion measurements (Haigh 1977). The uncertainty in an erosion pin method is typically at the 3 to 5 mm (0.12 to 0.20 in) level (equivalent to 36 to 60 t ha^{-1} [15 to 24 tn ac^{-1}] of soil erosion assuming a bulk density of 1.2 g cm^{-3})—not sensitive enough for most critical soil erosion measurements in agricultural or natural lands (Toy et al. 2002). Developments of contour plotting frame methods (Campbell 1974) and of laser scanner methods (Romkens et al. 1988; Huang and Bradford 1990) have eliminated some of the error sources associated with the volumetric methods and have improved the sensitivity in measuring soil erosion. Contour plotting frame and laser scanner methods, however, can only be applied to limited plot sizes (at most a few square meters) and have encountered difficulties in vegetation-covered lands. Furthermore, volumetric methods do not provide samples for analysis and thus miss out on the information pertaining to the property, such as the nutrient contents, of the eroded soil.

Fallout radionuclides such as ^{137}Cs, ^{210}Pb and ^{7}Be have been used as tracers to detect soil erosion and deposition (Ritchie and McHenry 1990; Walling 2002). Although limitations exist, these tracer techniques have been successfully applied in numerous studies that quantify soil erosion and deposition in natural landscapes (Walling and He 1997; Walling and He 1999; Peart et al. 2006). The fallout radionuclide techniques have been used to quantify relatively long term (i.e., 30 years) soil erosion and deposition rates. They are not suitable for short-term or individual soil erosion events due to sensitivity and background noise problems (Walling and Quine 1991; Quine 1995; Peart et al. 2006).

The most commonly used method for quantifying soil erosion is the runoff plot (RP) method (McDonald et al. 2003). Runoff-plot methods use artificial boundaries to define a plot area and direct runoff and eroded soil into a collector for soil erosion assessment. Runoff plots are sensitive classic dynamic methods for soil erosion research. They have been used extensively in the development of the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE). They are most suitable for ranking relative soil erosion among treatments in standardized plots (Mitchell and Bubenzer 1980). Runoff-plot methods, however, are not suitable for soil erosion measurements in undisturbed field conditions because their artificial boundaries alter the natural runoff pattern and thus may not represent natural runoff and soil erosion conditions.

A simple mesh-bag (MB) field method for soil erosion assessment has been available for some time (Hsieh 1992). The MB method is a dynamic method that involves installing small (e.g., 20 × 20 cm [7.9 × 7.9 in]) nylon mesh sheets in a plot to sample the redistribution of eroded soil after one or more runoff events. The nylon mesh sheets are installed intimately in contact with the contour of the bare ground (vegetation immediately beneath the bags is removed) so that they allow water but negligible amounts

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of soil particles to infiltrate underneath the bag. After one or more runoff events, mesh bags are harvested, and the soil on and within the sheets is collected for analysis. By design, the function of a MB is to sample the redistribution of eroded soil on a slope after runoff events (Hsieh 1992), with no intention to trap soil particles. That is, MB serve only to mark the original soil surface so that the redistribution of the eroded soil could be conveniently sampled. The amount of soil erosion is estimated by the weight of the eroded soil and the area of the bags. The MB method does not attempt to trap the eroded soil and thus causes little disturbance to the natural runoff pattern of a slope. It is suitable for field applications with flexible plot sizes and shapes. A previous study has shown that the MB method is sensitive (detection limit <0.1 t ha^{-1} [<0.04 tn ac^{-1}]) and reproducible in field applications (Hsieh 1992). However, several critical questions concerning the application and interpretation of the MB method have not been adequately addressed. For example, if the MB method estimates only the eroded soil that still remains on a slope, how does it account for the eroded soil that has been washed off the slope? In other words, what is the efficiency of the MB method in assessing total soil erosion? Does the bag size affect the performance of the MB method? These questions need be answered before the MB method can be applied for soil erosion studies.

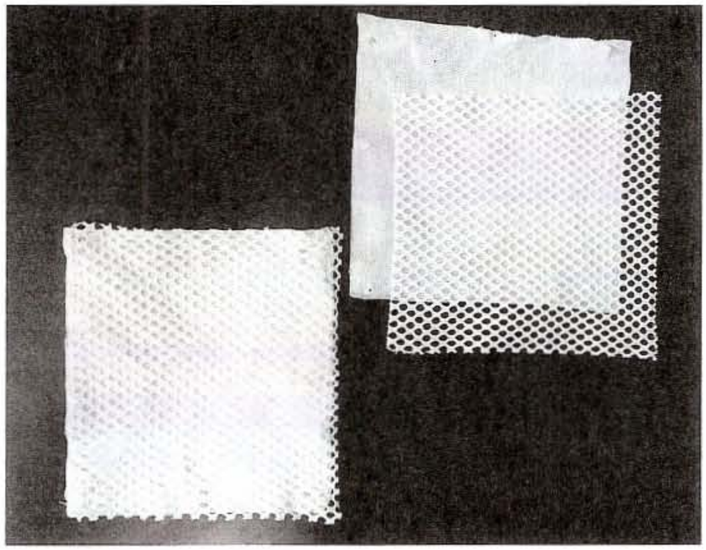
The lack of field soil erosion data has been a critical gap in soil erosion research, especially in larger field scales. This gap seriously limits our capability to understand, model, and predict soil erosion in agricultural and natural lands (Trimble and Crosson 2000; Nearing et al. 2000). This study was initiated to evaluate the efficiency of the MB method with a RP method and to establish a guideline for the application of the MB method in soil erosion studies.

Materials and Methods

Construction and Design of Mesh-bags. Mesh bags were constructed out of two nylon mesh sheets, one with ≈4 mm (≈0.16 in) mesh opening on the top to mimic the roughness of a soil surface and another with ≈0.1 mm (≈0.004 in) opening at the bottom to facilitate water infiltration (figure 1). For the concern of losing <0.1 mm (<0.004 in) fine particles through the bottom mesh, we conducted a prestudy test using a heavy clayey Illinois soil (Flanagan silt loam, fine, montmorillonitic Aquic Arguidoll) (USDA 2008). The clayey soil has 60.7% <0.02 mm (<0.001 in) particles and 20.8% <0.2 mm (<0.08 in) water stable aggregates. We installed six 15 × 15 cm (5.9 × 5.9 in) MBs on a level, bare soil surface. We then used a metal tube (9 cm [3.5 in] diameter and 15 cm [5.9 in] tall) to form a vertical circular boundary on top of each mesh bag by driving the tube slightly into the soil. We put 5 g (0.176 oz) of the clayey soil into each tube and applied an equivalent of 21 cm (8.3 in) rain by a sprinkler on the mesh bags. We harvested the mesh bags, dried the content, and weighed the clayey soil left on the bags. The soil left on the mesh bags was 4.91 ± 0.11 g (0.173 ± 0.004 oz) out of 5 g (0.176 oz) after the sprinkler rain. The <0.02 mm (<0.001 in) particles in the mesh-bag soil were 59.8% ± 1.8%, which is not significantly different from that of the original soil (60.7%). The results indicate that only a negligible amount of soil particles had passed through the bottom mesh. This is because (1) many fine particles were in aggregates larger than 0.1 mm (0.004 in), and (2) the mesh bags were installed intimately in contact with the bare soil surface. There is little space for fine particles to pass through, especially after the holes are filled. Both of the nylon mesh sheets were purchased from a local fabric store. Bag sizes from 10 × 10 to 30 × 30 cm (3.9 × 3.9 to 11.8 × 11.8 in) were tested in this study. The top and bottom sheets were aligned and stapled together to form a mesh bag before they were deployed in the field.

Figure 1

A mesh bag consists of a top nylon mesh with 4 mm opening to mimic soil surface roughness and a bottom nylon mesh with 0.1 mm opening to allow water infiltration. The top and bottom sheets are aligned to form a bag (left bottom in the picture) when applied in a field plot. The major function of a mesh bag is to mark the original soil surface before an erosion event so that the redistribution of the eroded soil after the event can be conveniently sampled.



Study Sites. Two study sites were used in this research. Site 1 is located at the Florida A&M University (FAMU) field in the main campus in Tallahassee, Florida. The soil of Site 1 is an Orangeburg loamy sand (Fine-loamy, kaolinitic, thermic Typic Kandiudults) (Sanders et al. 1981). Vegetation cover of Site 1 was mainly centipede grass (*Eremochloa ophiuroides*). Site 2 of the study is located at the FAMU Agricultural Experimental Station, 30 miles west of Tallahassee in Quincy, Florida. The soil in Site 2 is also an Orangeburg loamy sand (Fine-loamy, kaolinitic, thermic Typic Kandiudults) with mainly centipede grass vegetation cover.

The Bag-size Experiments. A 7 × 5 m (23.0 × 16.4 ft [width × length]) 35 m^2 (377 ft^2) plot was laid out on a relatively uniform 25% slope at Site 1. Prior to the experiment, vegetation cover within the plot was eliminated by clear cutting and herbicide spraying. Three mesh-bag sizes were tested in the experiments, i.e., 10 × 10, 20 × 20, and 30 × 30 cm (3.9 × 3.9, 7.9 × 7.9, and 11.8 × 11.8 in). Each bag size had six replicates. The 18 bags were installed randomly in a 1 m (3.3 ft) spacing grid in the plot. The bags were secured to the soil with four to eight metal nails so that the mesh sheets were in close contact and conformed to the contour of the soil surface. After one or more rain events, the mesh bags with soil on and within the sheets were collected, oven dried at 70°C (158°F) until constant weight, sieved through a 2 mm (0.08 in) sieve, and weighed. Soil erosion in a plot was assessed from the average weight of the <2 mm (<0.08 in) soil particles in the bags and the bag area in units of t ha^{-1} (Hsieh 1992). The experiments were repeated nine times during the 2005 rainy season.

Comparison Between the Mesh-Bag Method and the Runoff-plot Method. After the bag-size experiments, a trench alongside the downslope edge of the 7 × 5 m (23.0 × 16.4 ft), 25% sloped plot, was dug at Site 1. The trench was 7 m (23.0 ft) long, 70 cm (2.3 ft) wide and 80 cm (2.6 ft) deep. The trench was lined with heavy duty plastic liner for collecting the eroded soil from the plot. A 50 cm (1.6 ft) section of the plot immediately upslope to the trench was smoothed and covered with the plastic liner to serve as a corridor to direct the runoff water and eroded soil into the trench. Thirty-two 20 × 20 cm (7.9 × 7.9 in) mesh bags were laid out in the plot in a 1 m (3.3 ft) spacing grid pattern. After one or more rain events, the mesh bags were collected and processed similarly to those of the bag-size experiments. Subsamples of the <2 mm (<0.08 in) soil were also analyzed for particle size distribution (Day 1965), loss on ignition (600°C [1,112°F] for 2 h), total Kjehldahl nitrogen (Bremner and Mulvaney 1982) and total phosphorus (Olsen and Sommers 1982). Soil in the trench was also collected simultaneously with the collection of mesh bags. The soil in the trench was homogenized and weighed. Subsamples of the trench soil were oven dried at 70°C (158°F) to determine the moisture content and total dry weight of the collected soil. Trench soil samples were subjected to the same analyses as the mesh-bag samples. Besides the trench and mesh-bag samples, surface (0 to 2 cm [0 to 0.8 in]) soil samples within the plot were also collected using a corer. Twenty surface core samples were combined, homogenized, dried, sieved and analyzed the same as the previously mentioned samples.

Two gentle-sloped (on average 5%) and two moderate-sloped (on average 10%) runoff plots were installed on an originally grass-covered field at Site 2. The two gentle-sloped plots measured 4.3 × 4.9 m (14.1 × 16.1 ft) (21 m^2 [226 ft^2]) and 5.2 × 9.1 m (17.1 × 29.9 ft) (47 m^2 [506 ft^2]), while the two moderate sloped plots measured 6 × 4.5 m (19.7 × 14.8 ft) (26 m^2 [280 ft^2]) and 3.7 × 9 m (12.1 × 29.5 ft) (33 m^2 [355 ft^2]). Each plot had 10 cm (3.9 in) tall plastic boundaries installed at three sides of the plot. At the bottom (down slope) of each plot, a trench alongside the entire width of the plot was dug. The trenches were 80 cm (2.6 ft) wide and 95 cm (3.1 ft) deep to receive runoff water and eroded soil. The trenches were lined with heavy duty plastic liner. Similar to the setup at Site 1, a 50 cm (1.6 ft) section of the plot immediately upslope of the trench was smoothed, covered with the plastic liner, and secured with nails to serve as a corridor to direct the runoff water and eroded soil into the trench. Mesh bags of 15 × 15 cm (5.9 × 5.9 in) were installed in the plots in a 1 m (3.3 ft) spacing grid pattern. The mesh bags and the soil in the trenches were collected simultaneously after one or more runoff events. The bag and trench soil samples were processed and analyzed the same as the samples from Site 1. The Site 2 experiments were carried out five times during the 2007 rainy season and one time in 2008.

Statistical Analysis. Bag-size effect on soil erosion measurements was investigated using analysis of variance (ANOVA) (SAS Institute Inc. 2005). Linear regression was performed between MB and RP soil erosion measurements. Statistical significance for all analyses were tested at the 5% probability level. The spatial patterns of eroded soil and their soil organic matter contents were tested by looking at semivariogram data of four sampling periods. Semivariograms were calculated from 32 to 71 sampling points using the commercial Surfer 8 software program (Golden Software Inc. 2004).

Results and Discussion

The Bag-size Effect. Soil erosion measurements using three different mesh-bag sizes were taken during nine sampling periods. The amount of eroded soil assessed by the mesh-bag sizes ranged from as low as 0.4 to 1.4 t ha^{-1} (0.2 to 0.6 tn ac^{-1}) (May 7, 2005) to as high as 12.7 to 21.7 t ha^{-1} (5.1 to 8.8 tn ac^{-1}) (July 10, 2005) (table 1). The ANOVA and comparison of means indicate that bag size (i.e., 10 × 10, 20 × 20 and 30 × 30 cm [3.9 × 3.9 in, 7.9 × 7.9 in and 11.8 × 11.8 in]) had no significant effect on the amount of eroded soil assessed by the MB method in eight out of nine experiments (table 1). Only in one experiment (June 11, 2005) did the 30 × 30 cm size bags assess significantly (5% probability level) more eroded soil than the smaller-sized bags. Our results indicate that a mesh-bag size between 10 × 10 cm and 30 × 30 cm can be used to assess erosion by the MB method without significantly different results. We used a 15 × 15 cm (5.9 × 5.9 in) mesh-bag size in our other field experiment at the FAMU Quincy Experimental Station.

The Comparison between the Mesh-bag and Runoff-plot Methods. The MB and RP methods assess two mutually exclusive parts of soil erosion. The MB method assesses what was left in the plot, while the RP method assesses what was transported out of the plot. Soil erosion assessed by these methods are positively correlated (figure 2), regardless of rainfall conditions (total rainfall ranged from 14.1 to 580 mm [0.6 to 23 in]), slope (5%, 10%, and 25%), plot size (21 to 47 m^2 [226 to 506 ft^2]) and plot shape (square or rectangular) of the experiments. The amount of soil erosion assessed by the MB method was far more than that by the RP method in the 5% and 10% slope plots. The slopes of the regression lines in figure 2 represent the ratio (R) between the incremental increase of eroded soil estimated by the MB method and that by the RP method. For example, an R value of 7.1 in the 47 m^2 (506 ft^2) plot with a 5% slope suggests that for every incremental unit increase in the eroded soil transported out of the plot, there were corresponding 7.1 units increase in the eroded soil remaining in the plot. The R value, therefore, is related to the delivery ratio of the eroded soil in a plot and is a function of the slope and the size of the plot (figure 3). As demonstrated in figure 3, steeper slope and smaller plot size have smaller R values. Except in the steepest plot (25% slope) and the smallest plot (21 m^2 [226 ft^2]), the R value falls in the range of 5.5 to 7.1—indicating that the majority of the eroded soil remained in the plots even under quite severe runoff (90 to 210 mm [3.5 to 8.3 in]) conditions and limited plot size (26 to 47 m^2 [280 to 506 ft^2]).

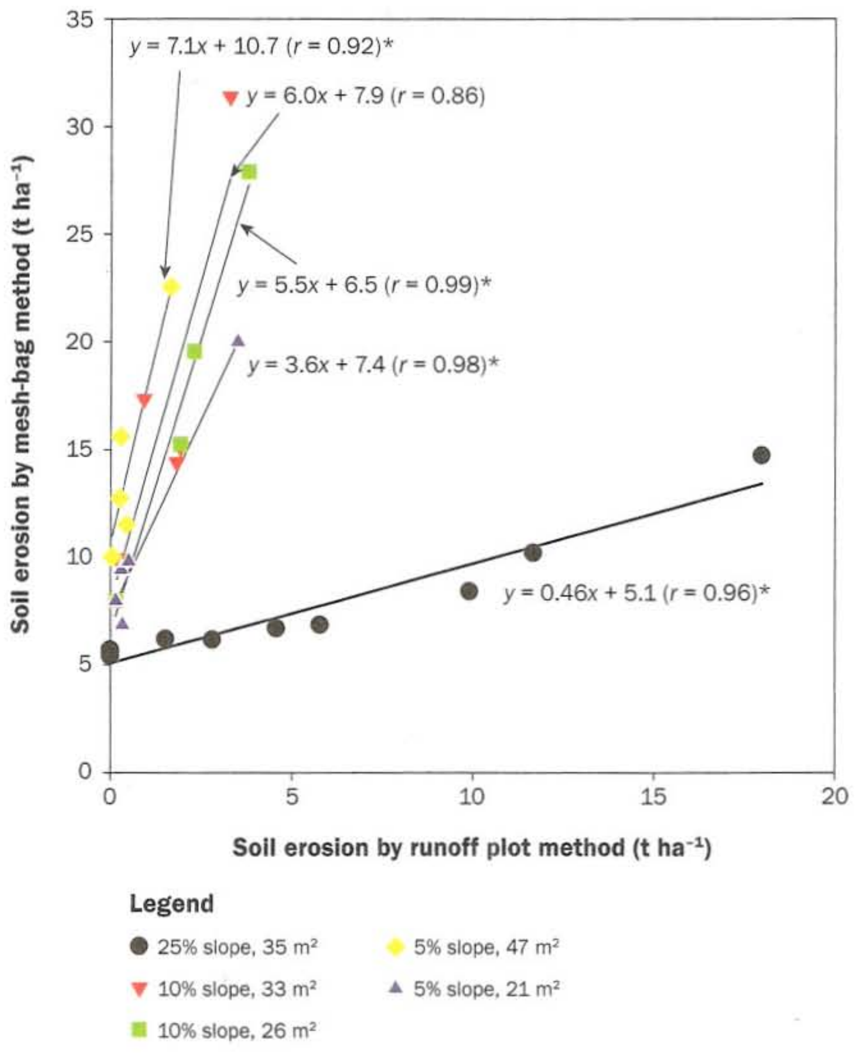
Three implications could be drawn from the above results:

1. In the 5% and 10% sloped plots, eroded soil was continuously generated during an

Table 1
Soil erosion (t ha^{-1}) assessed by three sizes of mesh bags deployed in the same plot during the 2005 rainy season. The values are means of six replicates. The same letter following the means in the same column designates no significant difference at the 5% probability level.

	Soil erosion by date								
Bag size	5/7 (t ha^{-1})	6/1 (t ha^{-1})	6/3 (t ha^{-1})	6/7 (t ha^{-1})	6/11 (t ha^{-1})	6/26 (t ha^{-1})	6/30 (t ha^{-1})	7/4 (t ha^{-1})	7/10 (t ha^{-1})
10 × 10 cm	1.4a	2.7a	1.8a	12.4a	7.8a	4.3a	0.6a	10.8a	12.7a
20 × 20 cm	0.6a	1.1a	0.9a	13.6a	7.8a	2.4a	0.3a	15.4a	13.1a
30 × 30 cm	0.4a	0.7a	0.8a	19.8a	17.7b	3.4a	0.2a	15.7a	21.7a

Figure 2
Relationships between the eroded soil assessed by the mesh-bag (MB) method and that by the runoff plot (RP) method. The MB method assesses the eroded soil that is still in a plot while the RP method assesses what is transported out of a plot. The linear regression and the null hypothesis of slope being zero were tested for significance at the 0.05 probability level. Significant regressions at $p < 0.05$ were denoted by the asterisk symbol. The correlation between the MB and RP methods for the 10% slope-33 m^2 plot was significant at $p < 0.1$. The residuals of regression were found to be normally distributed. The number of data points in each regression is 8 for the 25% slope-35 m^2 plot experiments and 5 for the rest of experiments.



erosion event, and the amount left in the plots was far greater than that transported out of the plots.

2. In the 25% sloped plot, a similar phenomenon occurred until the total erosion exceeded a certain extent (about 13 t ha^{-1} [5.3 tn ac^{-1}] in this case).

3. The MB and RP methods assess two mutually exclusive parts of the eroded soil: soil that remained in the plot (MB method) and soil that was transported out of the plot (RP method), and the total soil erosion in the plots should have been the sum of the two methods.

We shall discuss the third implication in detail in the later sections.

The Conservative Upper Limits of the Mesh-bag Method. The regression lines in figure 2 intersect the y-axis at positive values ranging from 5.1 to 10.7 t ha^{-1} (2.1 to 4.3 tn ac^{-1}). Those intercepts imply that until soil erosion exceeded 5.1 to 10.7 t ha^{-1} (as assessed by the MB method), soil erosion was not detected by the RP method. This, however, does not imply that runoff did not occur in those plots. We observed many times during the experiments that substantial runoff water was collected in the trenches of the plots but hardly any significant amount of the eroded soil was in them. This study shows that the MB method assesses not only splashed soil erosion but also runoff erosion to a large extent.

The intercepts of the regression lines in figure 2, therefore, represent not only the detection limit of the RP method but also the conservative upper limit of the MB method to quantify total soil erosion in a plot. This is because within those limits, virtually all the eroded soil was still in the plot, and the total soil erosion could be assessed by the MB method alone. Similar to the R ratio (figure 3), the conservative upper limit of the MB method is also delivery-ratio related and is a function of the slope and size of the plot (figure 4). Gentler-sloped or larger plots have greater conservative upper limits because the delivery ratio would be smaller with the

Figure 3

The ratio (R) between the incremental increase in eroded soil assessed by the mesh-bag (MB) method and that by the runoff-plot (RP) method, as a function of the slope and the size of the plot.

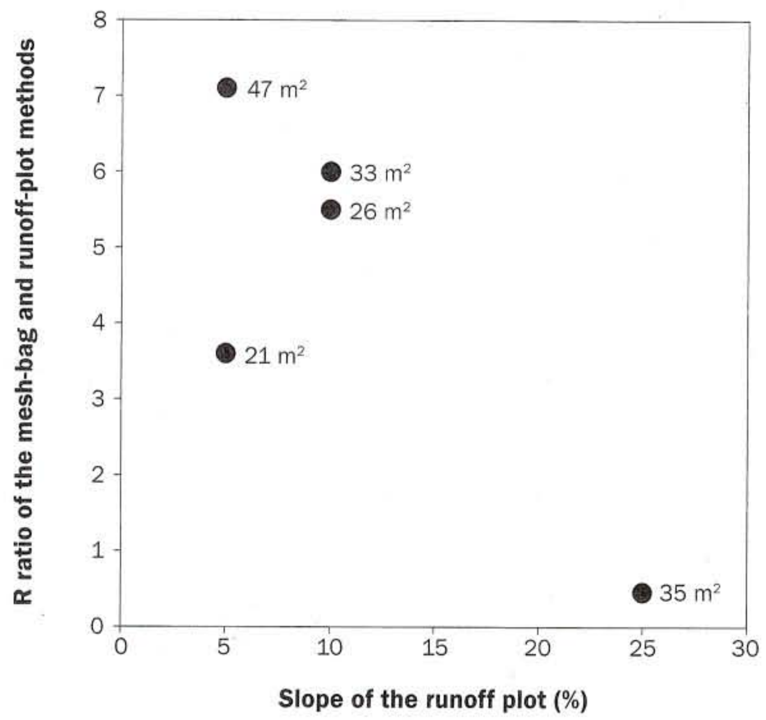
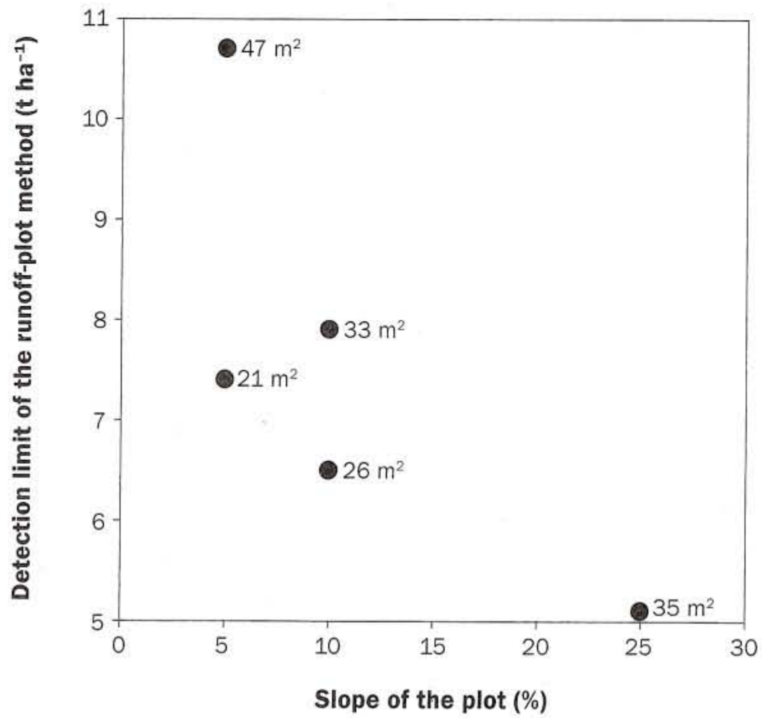


Figure 4

The detection limit of the runoff-plot (RP) method or the upper limit of the mesh-bag method as a function of the slope and the size of the plot.



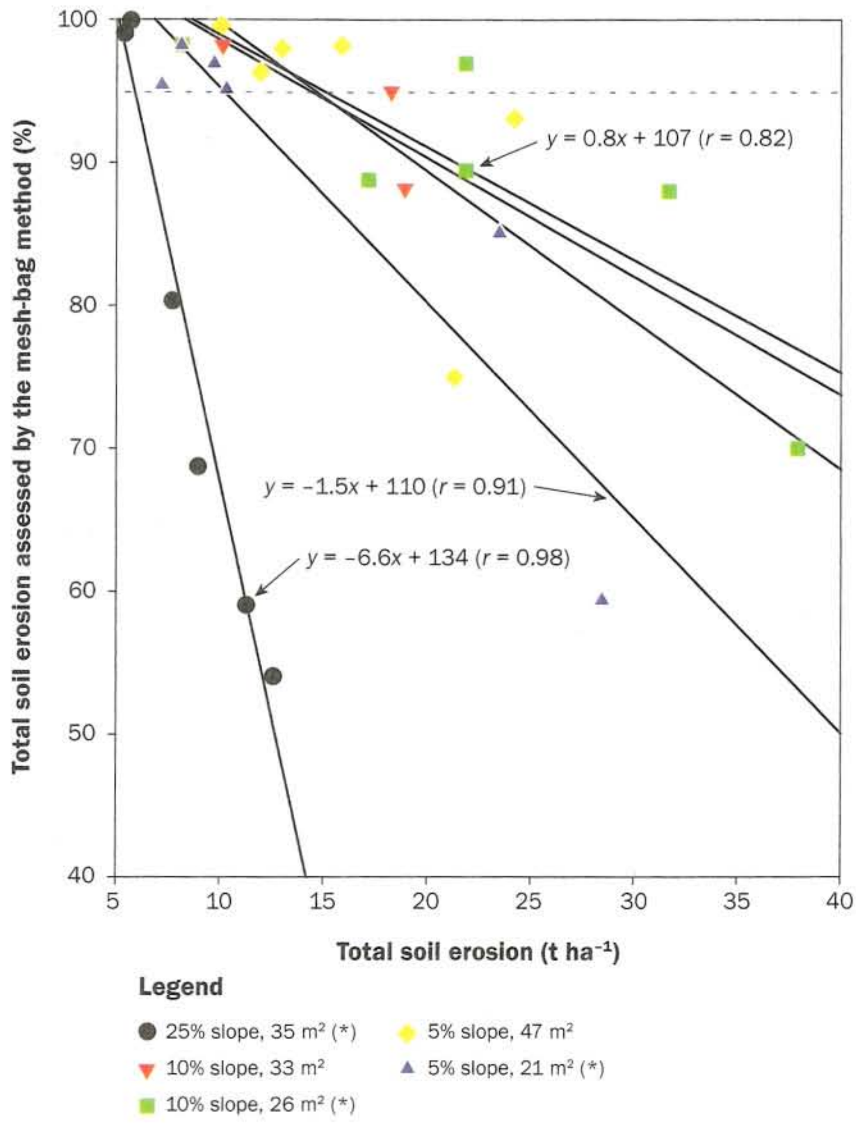
same runoff. The conservative upper limit of the MB method was 5.1 t ha^{-1} (2.1 tn ac^{-1}) in the 35 m^2 (377 ft^2) plot with 25% slope and 7.4 to 10.7 t ha^{-1} (3.0 to 4.3 tn ac^{-1}) in 21 to 47 m^2 (226 to 506 ft^2) plots with 5% to 10% slopes.

The Practical Upper Limits of the Mesh-bag Method. Since the total erosion in the runoff plots could be estimated by the sum of the MB and RP methods, we calculated the efficiency of the two methods, respectively, with regard to the total soil erosion. Figure 5 presents the efficiency of the MB method, in terms of <2 mm (<0.08 in) eroded soil, as the percentages of the total soil erosion estimated by the sum of the two methods. In the 25% sloped plot, the efficiency of the MB method decreased substantially as total soil erosion exceeded the conservative upper limit (5 t ha^{-1} [2.0 tn ac^{-1}]). In the 5% and 10% sloped plots, however, the efficiency of the MB method did not decrease significantly until total soil erosion exceeded the 15.5 t ha^{-1} (6.3 tn ac^{-1}) level. In fact, in the 5% and 10% sloped plots, the efficiency of the MB method remained above 80% in some cases, even when the total erosion exceeded 20 to 30 t ha^{-1} (8.1 to 12.1 tn ac^{-1}). If we take ≥95% efficiency as a practical threshold for the upper limit of the MB method to quantify total soil erosion, the practical upper limits of the MB method would be 6.5 t ha^{-1} (2.6 tn ac^{-1}) for the 35 m^2 (377 ft^2) plot with 25% slope, and 15.5 t ha^{-1} (6.3 tn ac^{-1}) for the rest of the plots except the smallest plot of 21 m^2 (226 ft^2), which had the practical upper limit of 11 t ha^{-1} (4.5 tn ac^{-1}). These practical upper limits of the MB method suggest a quite useful working range of the MB in gentle- to moderate-sloped lands to quantify total soil erosion. Toy et al. (2002) suggested that soil erosion exceeding 40 t ha^{-1} y^{-1} (16.2 tn ac^{-1} y^{-1}) is critical for conservation considerations. A working range of 15.5 t ha^{-1} per runoff event would cover most soil erosion events in gentle- to moderate-sloped lands.

In the 25% slope, the MB method has a lower upper limit of 6.5 t ha^{-1} (2.6 tn ac^{-1}) in a 35 m^2 (377 ft^2) plot. This upper limit could be extended to a larger value if a larger plot could be used. The size and shape of a MB plot are solely determined by the layout of mesh bags without any other physical structure requirement. Expansion of plot size in the MB method is relatively easy and simple. When laying out mesh bags in the field, we recommend that they roughly follow a regu-

Figure 5

The efficiency of the mesh-bag (MB) method to assess total soil erosion (<2 mm eroded soil) as a function of the amount of total soil erosion (<2 mm eroded soil). The dotted line represents the 95% efficiency. The linear regression and the null hypothesis of the slope being zero were tested for significance at the 0.05 probability level. Significant regressions were denoted by the asterisk symbol. The residuals of regression were found to be normally distributed. The number of data points in each regression is six.



larly spaced (e.g., 1 or 2 m [3.3 or 6.6 ft]) grid pattern rather than a random placement as suggested originally (Hsieh 1992). A regular-spaced grid sampling pattern would be best represented on an area basis rather than random or nested sampling patterns. The length of a MB plot should follow generally the direction of natural runoff, and the shape of the plot should follow the area of interest rather than a strict rectangular shape. On a watershed scale, the entire watershed could be subdivided into different regions depending on predetermined erosion class. Each region would have several randomly placed plots with a regularly spaced grid for the mesh bags. Using this sampling strategy, the eroded soil can be estimated for each erosion region, as well as for the entire watershed.

Application of the Mesh-bag Method to Quantify Soil Erosion. The MB method provides a simple yet sensitive means to quantify the redistribution of eroded soil in a plot. Based on that, the MB method can be applied to quantify soil erosion in at least two situations: (1) the MB method can be used as a convenient field method to compare the effect of conservation on soil erosion among different treatments or different parts of a landscape and (2) the MB method can be applied to study the relationship between the total soil erosion in a small watershed (or a catchment area) and the sediment yield. In the first situation, the MB application is similar to that of a RP method, except that the MB method does not disturb the natural runoff pattern in a field nor does it require the physical boundaries or processing of large amounts of soil sample as the RP method does. In this situation, the MB method should be carried out within the upper limits in order to ensure quantitative results. This study shows that in a field of less than 10% slope with light textured soil, the upper limit of the MB method is 15.5 t ha^{-1} (6.3 tn ac^{-1})

Table 2

Comparison of some physical and chemical properties of samples from the 0 to 2 cm surface soil of the plots, the runoff-plot method and the mesh-bag method. The same letter following the means in the same column designates no significant difference at the 5% probability level.

	Chemical properties			Physical properties		
Sample	LOI (mg g^{-1})	TKN (mg g^{-1})	TP (mg g^{-1})	Sand (%)	Silt (%)	Clay (%)
Surface soil, 0 to 2 cm	20 ± 9a	0.382 ± 0.113a	0.116 ± 0.045a	90.2 ± 2.3a	7.2 ± 2.9a	1.7 ± 0.9a
Runoff plot method	63 ± 32b	0.641 ± 0.504b	0.093 ± 0.057a	88.7 ± 7.6a	7.1 ± 5.9a	4.4 ± 2.7b
Mesh-bag method	16 ± 8a	0.332 ± 0.100a	0.076 ± 0.011a	96.6 ± 1.6b	1.2 ± 1.1b	2.2 ± 1.1a

Notes: LOI = loss on ignition. TKN = total Kjehldahl nitrogen. TP = total phosphorus.

in a relatively small plot (26 to 47 m² [280 to 506 ft²]). This study also shows that the upper limit of the method could be increased if the plot size is enlarged (figure 4). We did not determine the MB upper limits beyond 47 m² (506 ft²) or in a heavier textured soil; therefore, they have to be determined separately. A simple and practical way to decide approximately whether the MB upper limit has been exceeded is by installing a silt fence at the bottom of a MB plot that catches soil particles from approximately the same runoff area. If the amount of the eroded soil collected in the silt fence during a measurement is not significant, say <5% of what is estimated by the MB on a plot area basis, the upper limit of the MB method has not been exceeded.

The second situation in which the MB method can be applied to quantify soil erosion is in studying the relationship between the soil erosion in a small watershed (or a catchment area) and the sediment yield. Unlike the first situation in which the MB method had to be applied within the upper limit, in the second situation there was no upper limit since the eroded soil that leaves the watershed or catchment area can be quantified by sediment yield in the streams or by a silt fence. The sediment yield in the streams (or in a catchment area), however, must be observed simultaneously with the MB method.

The MB method was originally designed to sample the redistribution of eroded soil without trapping the eroded soil. This is important because once trapping soil is involved, the natural runoff pattern in the field may be altered, and the source area of the eroded soil sampled by a bag would be impossible to estimate (Hsieh 1992). The no-trapping strategy of the MB method enables the mesh bag to be a true field method.

Properties of the Eroded Soil. Besides the amount, the chemical and physical properties of the eroded soil are also important in soil conservation studies. Table 2 shows comparisons of some chemical and physical properties of soil samples from the 0 to 2 cm (0 to 0.8 in) surface soil of the plots, the RP method, and the MB method. The organic matter, total Kjehldahl nitrogen, and total phosphorus concentrations of the soil samples by the MB method were not significantly different from those of the 0 to 2 cm (0 to 0.8 in) surface soil of the plots, even with the greater amounts of sand in the eroded soil of the MB method. On the other hand, the organic matter and total nitrogen concentrations of the RP method were significantly higher (at 0.05 probability level) than those of the 0 to 2 cm surface soil of the plots. Apparently, the samples of the RP method represent what was differentially washed out of the plot and enriched with organic matter and total nitrogen in comparison to the surface soil. This would indicate the association of organic matter and total nitrogen with the clay in the eroded soil of both the RP and MB methods. Higher organic matter contents associated with clay particles were observed in other studies (e.g., Fullen et al. 1996). The particle size distribution of the eroded soil of the MB

Figure 6

The efficiencies of the mesh-bag (MB) method to assess total eroded soil (<2 mm soil), the concentrations of organic matter, total phosphorous, and total Kjehldahl nitrogen as a function of total soil erosion. The dotted lines represent the 95% efficiency.

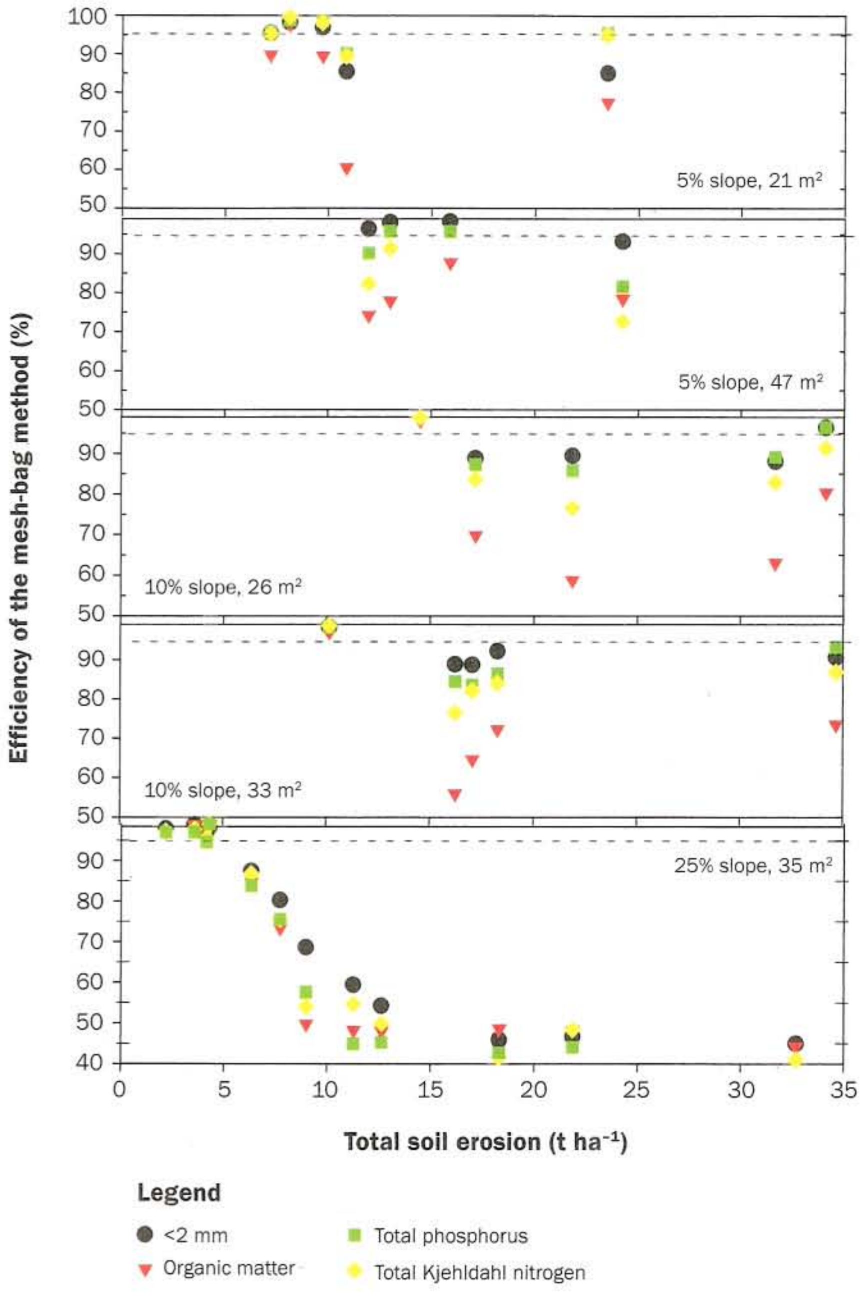
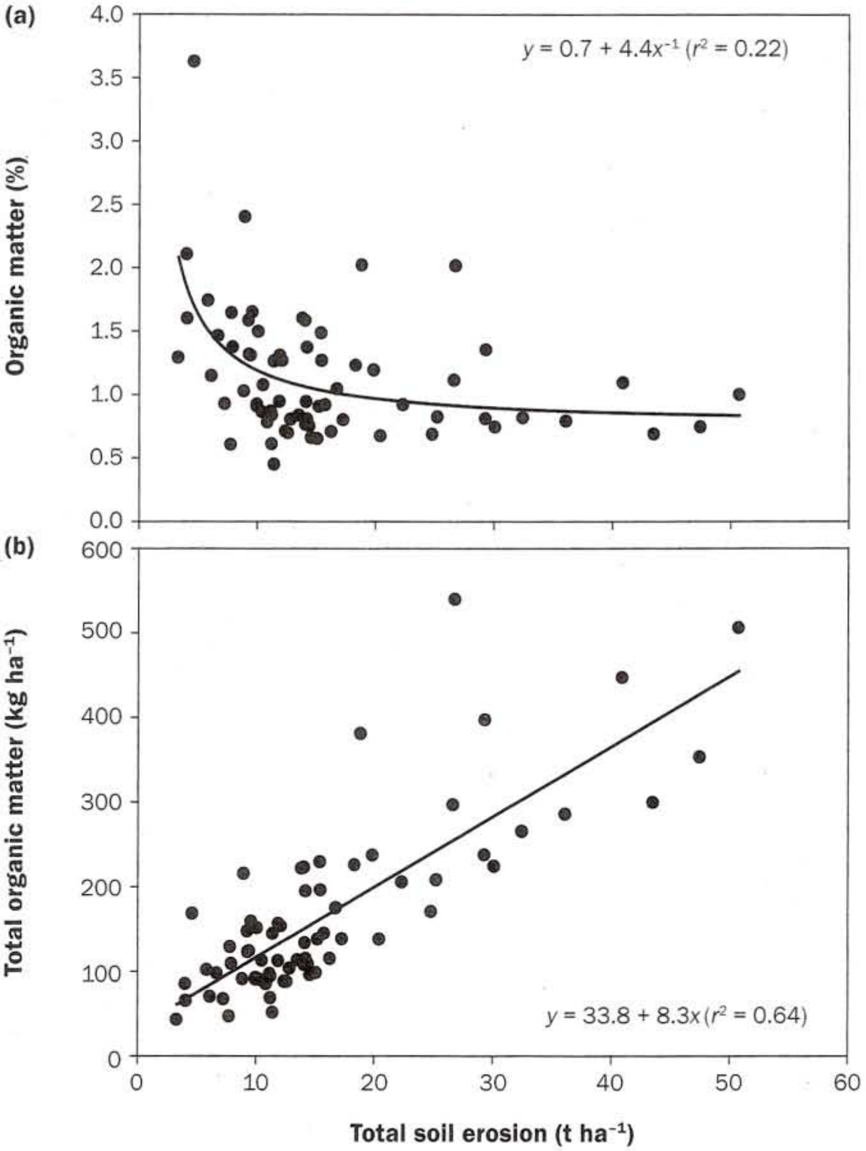


Figure 7

(a) Correlations between the eroded soil (<2 mm) and the concentration of organic matter (OM) and (b) correlations between eroded soil and the total amount of organic matter distribution in the 47 m² plot with 5% slope during the soil erosion event of October 29, 2007, to February 25, 2008. Significant correlations between eroded soil and organic matter concentration and between eroded soil and total amount of organic matter were observed at $p < 0.05$.



method was significantly coarser than that of the RP method. A sorting effect of the runoff apparently was the cause of this textural difference. Larger particles such as sand tend to be settled first, and finer particles such as silt or clay can travel further and move along with the runoff for a longer distance.

We calculated the efficiencies of the MB method to assess soil organic matter, total nitrogen, and total phosphorus associated with the total eroded soil and presented the results in figure 6. When the total soil erosion was within the practical upper limit of the MB method (i.e., 6.5 t ha^{-1} [2.6 tn ac^{-1}] for the 35 m^2 [377 ft^2] plot with 25% slope, 15.5 t ha^{-1} [6.3 tn ac^{-1}] for 26 to 47 m^2 [280 to 506 ft^2] plots with 5% to 10% slopes), the efficiency of the MB method to assess soil organic matter, total N and total P was similar to that of the <2 mm (<0.08 in) surface soil. As the soil erosion increased significantly beyond the practical upper limit of the MB method, the efficiency of the MB to assess soil organic matter became significantly less than that of the <2 mm surface soil in the 5% and 10% plots. This is an indication of preferential transport of the soil organic matter out of the plot (figure 6) ahead of the <2 mm soil in those plots. The preferential transport of total nitrogen and total phosphorus with respect to the <2 mm surface soil, however, was not as pronounced, probably because most nitrogen and phosphorus were aggregated with the <2 mm mineral particles while those preferentially transported organic plant debris were nitrogen and phosphorus depleted. These results confirm that the MB method can assess representative total nitrogen and total phosphorus of the eroded soil when the erosion is within the practical upper limit of the MB method.

Spatial and Temporal Patterns of Eroded Soil Distribution. Spatial variation in soil erosion is an important factor to be considered in soil erosion research, and it needs to be addressed accordingly (Johnson and Gordon 1988; Morin and Kosovsky 1995). The MB method can provide spatial and temporal variability of eroded soil distribution within a plot or within a landscape. However, from our analysis of semivariograms of the eroded soil distribution, we cannot prove the presence of spatial dependence or that the eroded soil distribution had a pattern.

The MB method also provides information pertaining to the correlation among the eroded soil and its chemical and physical properties. Figure 7 presents the correlations between the eroded soil and its organic matter concentration and between the eroded soil and the total organic matter content in the 47 m^2 (506 ft^2) plot with 5% slope. The <2 mm (0.08 in) eroded soil correlates inversely with the organic matter concentration but correlates positively with the total organic matter content (figure 7). This result is expected because heavily eroded soil may come from deeper soil profile, which tends to be organic matter depleted in comparison to the top soil. The total amount of soil organic matter (not the concentration) associated with the eroded soil, however, was still proportional to the amount of soil eroded (figure 7b).

Summary and Conclusions

We confirmed in this study that the soil erosion assessed by the MB method is positively correlated with that of the RP method in the same plot under the same runoff event even though the methods assess two mutually exclusive parts of total soil erosion. The MB method assesses what remained in a plot whereas the RP method assesses what is transported out of a plot. The MB method assessed a much greater amount of soil erosion than the RP method in the 5% and 10% slope plots, indicating that only limited portions of the eroded soil was transported out of a plot in each erosion event. The MB method can quantitatively assess soil erosion to the extent that the majority of the eroded soil is still in a plot. This extent of soil erosion is the upper limit of the MB method, and it is a function of the size and slope of the plot. We determined the practical upper limit of the MB method to be 15.5 t ha^{-1} (6.3 tn ac^{-1}) in plots of 26 to 50 m^2 (280 to 538 ft^2) with 5% and 10% slopes and 6.5 t ha^{-1} (2.6 tn ac^{-1}) in the plot of 35 m^2 (377 ft^2) with 25% slope. The upper limits of the MB method increase as the plot size becomes larger or the slope becomes gentler. The MB method can be applied to quantify soil erosion in field conditions in at least two situations: (1) to compare conservation effect on soil erosion with various treatments or with various parts of a watershed, and (2) to determine the relationship between the total soil erosion and sediment yield in a watershed (or a catchment area) by simultaneously measuring the eroded soil that is transported out of a field using sediment traps, stage-level approach, or a silt fence at the outlet of a catchment area. Mesh-bag sizes ranging from 10 × 10 to 30 × 30 cm (3.9 × 3.9 to 11.8 × 11.8 in) had no significant effect on the amount of soil erosion assessed. The MB method is a simple, sensitive, and quantitative field method that can be applied to a wide range of agricultural and natural lands. The spatial and temporal patterns of soil erosion and the resulting nutrient movements revealed by the MB method could give us valuable insights into the soil erosion processes under natural field conditions.

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