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Lecture Note

Measuring erosion and sediment yields on slopes and in small catchments

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Measuring erosion and sediment yields on slopes and in small catchments

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1. Introduction

Soils are crucial to life on Earth. There are many functions and ecosystem services performed by soil: 1) Soils support plant growth, by providing habitat for plant roots and nutrient elements for the entire plant. 2) Soils regulate water supplies. Water loss, utilization, contamination, and purification are all affected by the soil. 3) Soils function as nature's recycling system. 4) Soils are alive and are home to creatures from small mammals and reptiles to tiny insects to microorganisms of unimaginable numbers and diversity. 5) Soils markedly influence the composition and physical condition of the atmosphere by taking up and releasing large quantities of carbon dioxide, oxygen, and other gases and by contributing dust and re-radiated heat energy to the air. 6) Soil plays an important building material in the form of earth fill and bricks (baked soil material), and provides the foundation for virtually every road, airport, and house we build (Brady and Weil, 2002).

In earth science, soil erosion is the action of surface processes (such as water flow or wind) that remove soil, rock, or dissolved material from one location on the Earth's crust, and then transport it to another location. Commonly seen soil erosion forms include water erosion, wind erosion, tillage erosion, glacial erosion, streambank erosion, chemical erosion, and etc.

If without the influence of human activities, soil erosion can take place naturally. This is geological erosion (Figure 1). It wears down hills and mountains, and subsequently deposits eroded sediments into valleys, lakes, and bays. In most settings, geological erosion wears down the land slowly enough that new soil forms from the underlying rock or regolith faster than the old soil is lost from the surface. Accelerated erosion occurs when people disturb the soil or the natural vegetation by overgrazing livestock, cutting forests for agricultural use, plowing hillsides (Figure 1), or tearing up land for construction of roads and buildings. Accelerated erosion is often 10–1000 times as destructive as geological erosion, especially on sloping lands in regions of high rainfall (Brady and Weil, 2002).

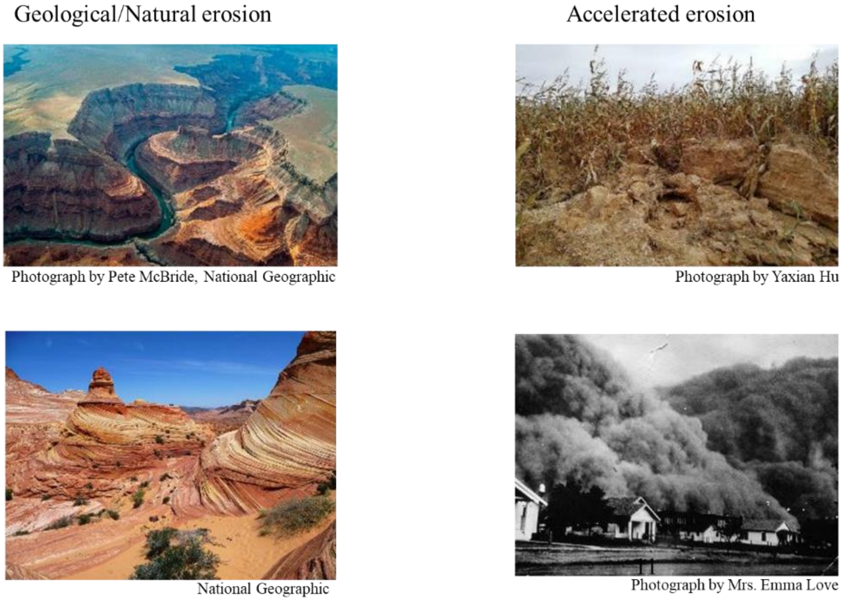

Figure 1 Geological vs. Accelerated Erosion.

To effectively control soil erosion, we need to: 1) identify the most susceptible regions, seasons or more specific conditions (soil type, coverage, tillage, etc.); 2) establish and apply soil conservation measures; 3) use modeling to predict soil erosion risk in the future. All starts with by measuring and recording. In this report, we first introduce some widely applied methods to measure water and wind erosion, and then illustrate some new techniques that have great potential to improve the spatial resolution or expand the temporal scale of current understanding of soil erosion. Most of the materials presented in this report are based on the experiences collected by Baoyuan Liu, and supportive materials from some highly reputed books (Brady and Weil, 2002; Hudson, 1995; Morgan, 2005; Wischmeier and Smith, 1978).

2. How to measure water erosion?

2.1 Water erosion measurements at different scales

1) Microplot

Micro-plot is to measure rain splash. Such research was originated from Ewald Wollny in 1882, who used a splash board of 80 cm * 80 cm to capture soil particles trajectories splashed from soil surface when subjected to raindrop impacts (Figure 2). Moreover, to measure rain splash, there are also Ellison splash dish, Ellison splash board and Morgan splash cup. They are the pioneers in detecting rain splash.

According to Stallings (1957), "…The discovery that raindrop splash is a major factor in the water erosion process marks the end of one era in man's struggle with soil erosion and ushers in another which, for the first time, holds out hope for a successful solution to the problem. The exact nature of the effects of raindrop splash is the phase of the water erosion process that escaped detection during the first 7000 years of civilization. It explains why the efforts at protecting the land against scour erosion these 7000 years have failed. It explains why there is little or no erosion on land with ample plant cover. It explains many things that have puzzled agricultural leaders and practitioners throughout this long and troublesome period…"

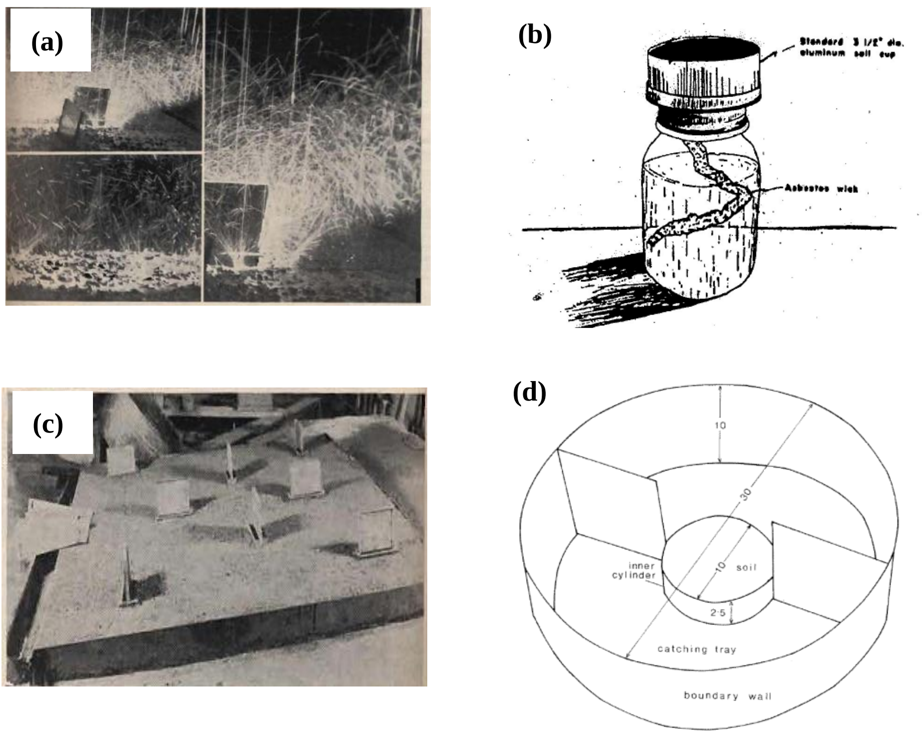

Figure 2 Different micro-plots to measure erosion caused by rain splash. (a) Ewald Wollny splash board; (b) Ellison splash dish; (c) Ellison splash board; (d) Morgan splash cup.

2) Bounded plot

Bounded plots (often rectangular) are often employed at permanent research or experimental stations to study the factors affecting water erosion (Figure 3). Each plot is a physically isolated piece of land of known size, slope steepness, slope length and soil type from which both runoff and soil loss are monitored. The plot edges are made of sheet metal, wood or any material that is stable, does not leak and is not liable to rust. The edges should extend 150-200 mm above the soil surface and be embedded in the soil to a sufficient depth so as not to be shifted by alternate wetting-and-drying or freezing-and-thawing of the soil. The standard plot (or unit plot) is 22 m long and 1.8 m wide, although other plot sizes are sometimes used (Morgan, 2005). In our country here in China, we standardized it with our metric system as 5 m × 20 m = 100 m^2.

Figure 3 Bounded plots built from bricks and metals.

Before introducing different forms of bounded plots, we must first understand the most widely applied soil erosion model: Universal Soil Loss Equation (USLE). In this model, it is assumed that the soil loss from a certain area is a combined result from different factors: Rainfall erosivity (R) represents how erosive local rainfall is; soil erodibility (K) dictates how erodible or easily susceptible to erosion one soil is; slope length (L) and slope steepness factor (S) reflect the influences of local terrain features; cover management factor (C) represent what kind of cover management and how much they affect soil loss; support practice factor (P) how how different practices, such as terraces, grass waterways, and contour tillage, affect soil loss.

When dating back to the history of this equation, we know that the equation was established from a great number of data measured and recorded over all the US and other regions of the world. To be comparable among different measurements and studies, the erosion plots were often standardized into a unit plot (or a standard plot) with a slope gradient of 9%, length of about 20 m, staying fallow with up and down slope tillage, and no conservation practices. On the applied side, when all the slope length, steepness, cover management and practices meet the above-described conditions, the L, S, C, and P each equals 1, and the USLE equation can then be used to calculate soil erodibility by dividing the average soil loss with rainfall erosivity (Wischmeier and Smith, 1978). Therefore, it is essential to maintain the slope length, steepness, cover management and practices exactly as required above. Otherwise, as shown in Figure 4, it was a unit plot at the beginning, but had not been ploughed for years. The soil surface conditions were thus different from fallow soil required in the unit plot, and thus cannot be used to estimate soil erodibility factor.

Figure 4 Bound plot originally built as unit (standard) plot but later abandoned.

If not for calculating erodibility factor for local soils, but for other purposes, bounded plots can also have different slope lengths to evaluate how short and long slopes affect soil erosion processes (Figure 5a). You can also build up bounded plots with different slope gradients to compare the soil losses from flat or steep slopes (Figure 5b). If you would like to compare the potential influences of different tillage practices or coverage on soil loss, you can also build up bounded plots managed in different ways (Figure 5c). Moreover, if you have specialized research questions, such as non-point source pollution, you can also design the bounded plot with sections as needed (Figure 5d).

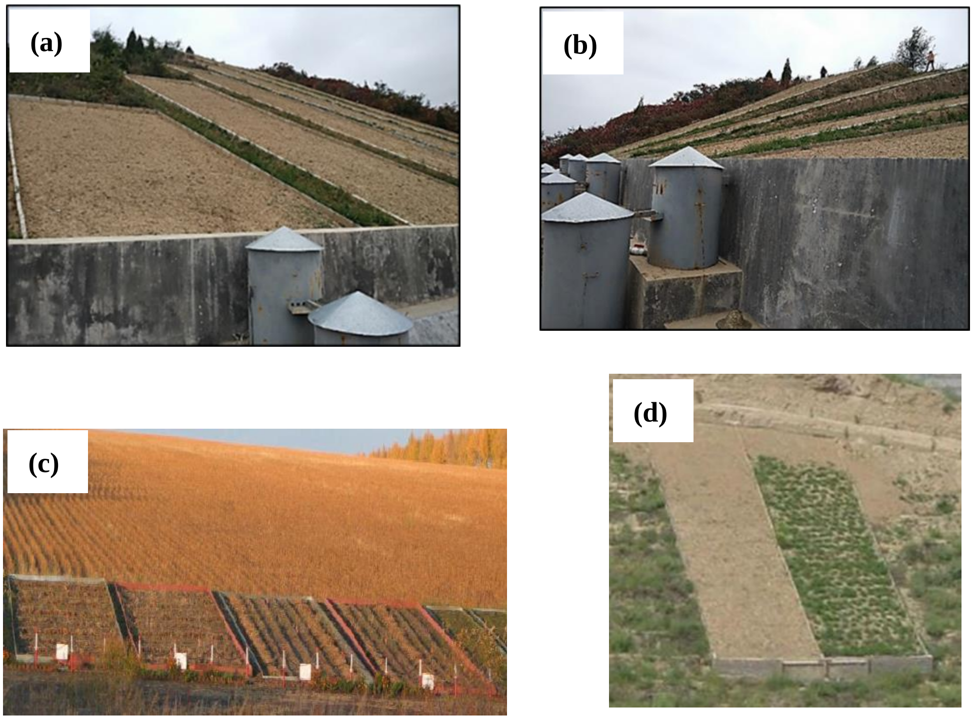

Figure 5 Bound plots with different slope lengths (a), slope steepness (b), tillage practices (c) and coverage (d).

For a bounded plot, there are different components (Figure 6). The most obvious part is the plot bounded by bricks or metals. Then, we need a group of sediment tanks connected with the outlet at the lower end of the plot, to collect runoff and sediment discharged out of the plot. To do so, we also need a trough to channel the runoff and sediment into the lower-lying sediment tank.

Figure 6 Bounded erosion plot and its components (adopted from Morgan, 2005).

The trough should be reasonably aligned with the lower wire of the bounded plot, to ensure a continuous discharge of runoff and sediment. Otherwise, soils on the eroding slope are likely to collapse over into the trough and the erosional soil loss will then be overestimated. Meanwhile, the trough cannot be too wide, otherwise eroded sediments are apt to stay in the big area of the trough instead of being discharged out of the plot into the sediment tank. This will then lead to an underestimation of erosional soil loss. When big rainstorms occur, they often produce large amount of runoff and sediment. The suspension overflow from a first sediment tank is then pass through a divisor, which splits the flow into equal parts and passes one part, as a sample, into a second collecting tank (Hudson, 1995). Different designs of sediment divisor are illustrated in Figure 7.

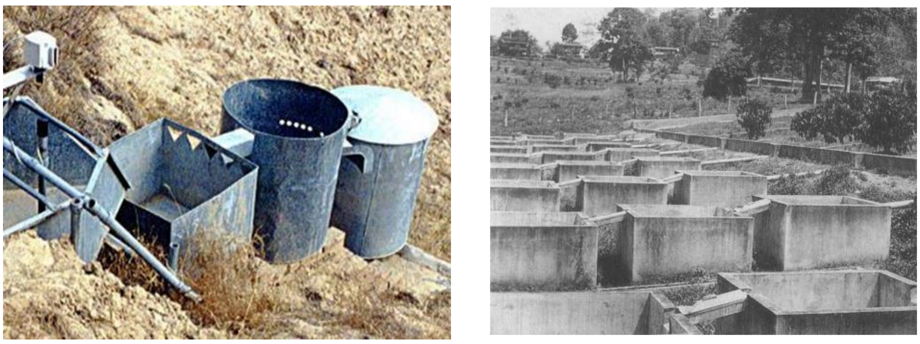

Figure 7 Different designs of sediment divisor (adopted from Hudson 1995).

After the rainstorm, we need to sample sediment out of the sediment tank to measure sediment concentration. However, sediment particles can settle through water and thus are prone to have larger concentration at the bottom than at the upper layer. Even after stirring, it is nearly impossible to ensure the sediment suspension is well blended (Figure 8a). Here we introduce a column sampler (Figure 8b), which can sample a sizable column of suspension from the sediment tank, efficiently overcoming the bias by the conventional manner.

Figure 8 A sediment tank full of sediment suspension (a), and a column sampler (b).

2) Field scale

When investigating soil erosion at field scale, we often need to measure and collect sediment samples generated from larger area with much more amount, typically as demonstrated in Sampson in Utah since 1912, about 10 acre (4 km^2) in the US, or Zizhou in China since 1963, about 1.72 km^2. Normally, an H-flume is employed because it is non-silting and unlikely to become blocked with debris. Sometimes, an ultrasonic water level meter is installed to detect runoff and the data is automatically saved in the logger. Sediment concentration can also be measured by a turbidity meter (Figure 9). For smaller field, we can use smaller sized H-flume. However, the turbidity meter cannot detect large sediment concentration beyond its scale, and thus is not applicable for regions often susceptible to severe soil loss (Figure 9).

Figure 9 An instrumented H-flume.

To efficiently record and collected sediment, one of the commonly seen divisor in the field is the Coshocton wheel (Figure 10a), with a collector on the rotating wheel to selectively collect a part of the sediment for further analysis (Hudson, 1995). In most cases, an automatic sediment sampler is installed at the bottom of the H-flume to extract samples of the runoff at regular time intervals during the storm for later analysis of its sediment concentration. The time each sample is taken is also recorded (Morgan, 2005). However, sediment can settle into the bottom layer of the runoff suspension. Therefore, to collect sediment samples across the entire flow layer, we often combine the sediment sampler with a foam-like material of light-density, to help the sediment sampler to float as the overflow increase (Figure 10b).

Figure 10 Coshocton wheel (a) and floatable sediment sampler (b).

Thanks to programable devices, sediment measurement and sampling in the field can be further improved by installing an autosampler such as ISCO (Figure 11a). The sampling rotation intervals are programmable as you need, and the samples can then be collected in the bottles and weighed to calculate sediment concentration. Another type of autosampler is designed based on a volume-mass conversion relationship, namely that sediments are heavier than water. At predetermined time intervals, the weight of the sediment suspension collected in the tank can be recorded to determine the exact volume and mass of the sediment-laden water. Since the tank is reversible, it can be emptied after weighing and ready for next round of sediment collecting and weighing, thereby allowing the implementation of real-time measurement and synchronous calculation of runoff rate and sediment concentration in the field (Figure 11b) (Zhan et al., 2021).

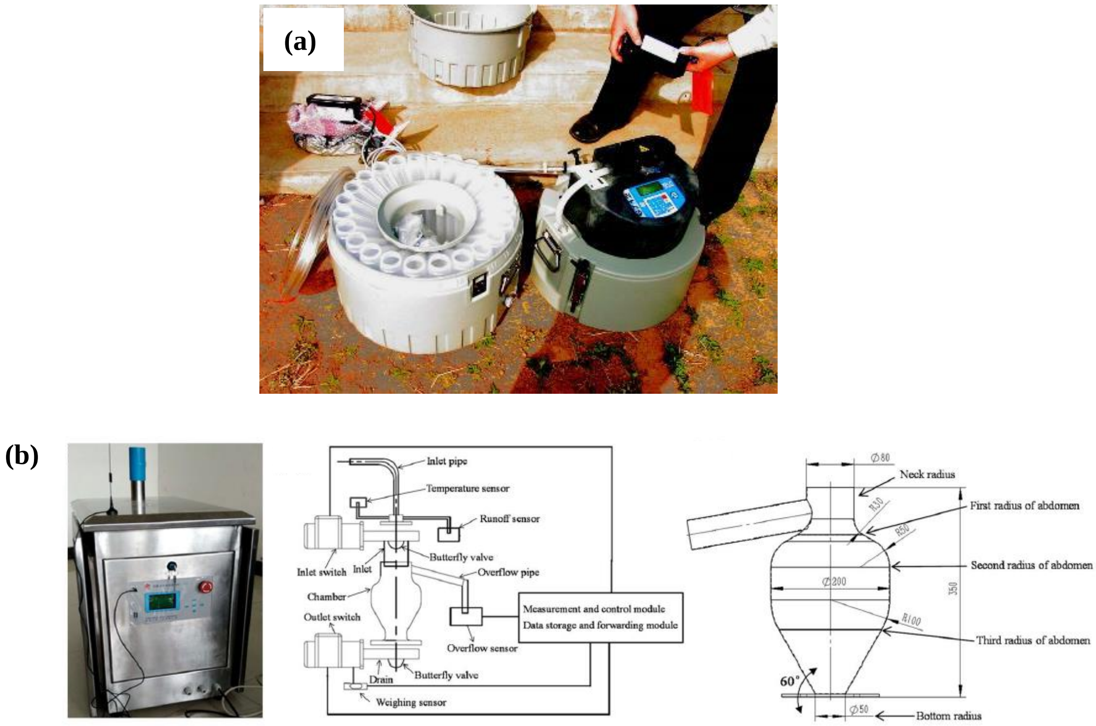

Figure 11 ISCO sediment autosampler (a) and reversible sediment autosampler (b) (adopted from Zhan et al., 2021).

4) Small catchment

When coming to even larger scale, a small catchment (often defined as 40000-250000 acre in the US or smaller than 50 km^2 in China), the flow measurement is often materialized by weirs (Figure 12). Weirs can have different shapes, depending on the landscape features. They often have meters on the sidewalls or recording stations so that we can calculate the flow rate by reading the flow height and applying it to the stage-discharge relation. Water samples are taken at set times with specially designed integrated sediment samplers, or the sediment concentration is monitored continuously by recording the turbidity of the water. With measurements made at set times, there is a need to extrapolate the data to cover the period between samples. The standard approach is to establish a sediment discharge rating curve in which the sediment concentration (C) is related to the water discharge (Q) by the equation: $C = a*Q^b$ (Morgan, 2005).

Figure 12 Typical weirs used on the Chinese Loess Plateau.

The accuracy of this method is highly dependent on the frequency of sampling. The likelihood of underestimation increased as the sampling frequency decreased, since, with longer sampling intervals, the record is likely to include fewer flood events. It should also be recognized that the turbidity meter does not give a true record because the measurements are subject to errors associated with influence of the particle size of the sediment load, the magnitude of the sediment concentration, the presence of organic matter and the need to keep the sensors clear of algae. Despite these problems, the method is currently the best available to provide estimates of suspended sediment yield, especially if high frequency data are needed. Meanwhile, because of the need for regular calibration and maintenance, such data come at greater cost compared to using rating curves (Morgan, 2005).

2.2 Commonly applied methods to improve soil erosion measurement

Apart from conventional erosion plots and weir measurement, sometimes we also would like to improve soil erosion measurement under the help of engineering design or advanced technologies. Here we introduce two commonly applied methods that can be of great help to expand the spatial and temporal range of soil erosion investigation.

1) Rainfall simulation

Field plot experiments depend upon natural rainfall which is always unpredictable and frequently perverse. For many years, research workers have sought to be independently by using a man-made simulation of rainfall. This has two advantages: the speed of research is greatly accelerated since the results are no longer dependent upon waiting for the right kind of rain to come at the right time, and also the efficiency of the research is increased by control of one of the most important variables, rainfall. It is no longer necessary to interpretate or extrapolate from storm to storm – the same storm can be created over and over until the results have been tested and confirmed. Another minor advantage is that it is usually quicker and simpler to set up a simulator over existing cropping treatments than to establish the treatments on runoff plots (Hudson, 1995).

To simulate rainfall events, the equipment must meet the basic requirements as listed here: 1) able to simulate the desired rainfall intensity; 2) the size, terminal velocity, kinetic energy and drop impact angles of the simulated raindrops should be similar to that of natural raindrops; 3) the simulated raindrops should have even spatial distribution over the subject area; 4) if needed, there should be shield to protect falling drops from wind; 5) the entire equipment should be easy to operate.

The simulated raindrops are made from nozzles under a low static head of water or pumped through nozzles under pressure. Depending on the specific requirements on drop size, distribution pattern and coverage area, we can choose different nozzle tips (Figure 13a, 13b). Very often, to achieve full coverage over the study area, we need to align nozzles with overlapped area (Figure 13c). Therefore, the actual rainfall intensity and spatial variation of simulated rainfall must be carefully calibrated before using.

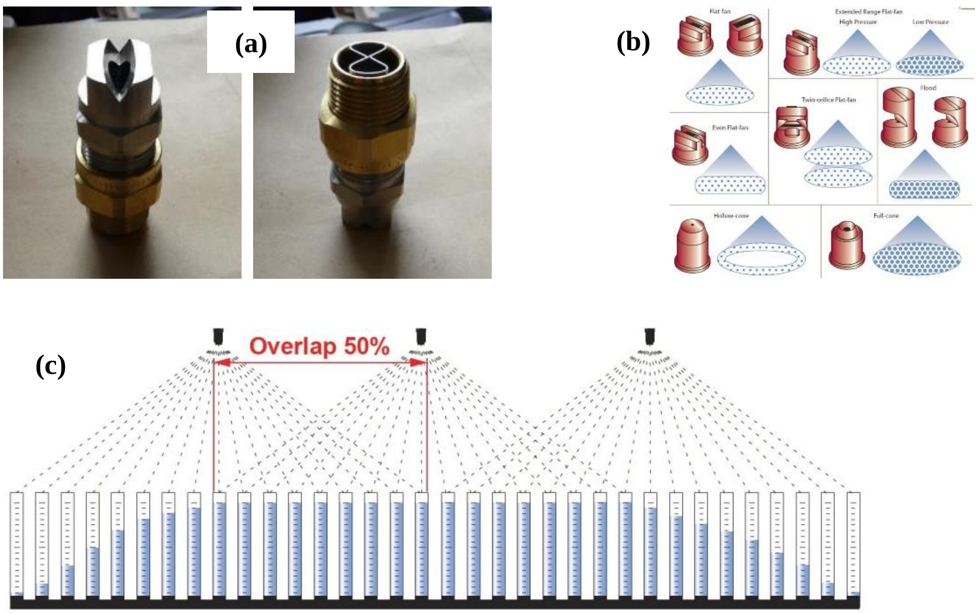

Figure 13 Different nozzle tips (a), their spray patterns (b) and the rainfall intensity distribution under overlapped nozzle tips (c).

The rainfall simulation can be installed indoors in a hall, with tall enough falling height for water drops to reach terminal velocities (Figure 14a). The hall also needs to be spacious enough to limit spatial unevenness of raindrop distribution. In this way, the simulated rainfall with designed intensity and duration can be repeatedly applied to small or large flumes to carry out comparison studies indoors. If combined with transformable flumes, which can have different gradients, slope patterns, widths, lengths and etc. (Figure 14b), it will largely expand the possibilities of soil erosion scenarios. There is also portable rainfall simulation equipment that can be reassembled wherever needed in the field (Figure 14c, 14d). The nozzle layout can change depending on local slope conditions; the rainfall intensity can be controlled by panels; the runoff and sediment can be collected from troughs and sediment tanks; the power and water supply can be managed by motors and portable water tanks; and it is easy to disassemble and back up for long-distance transport.

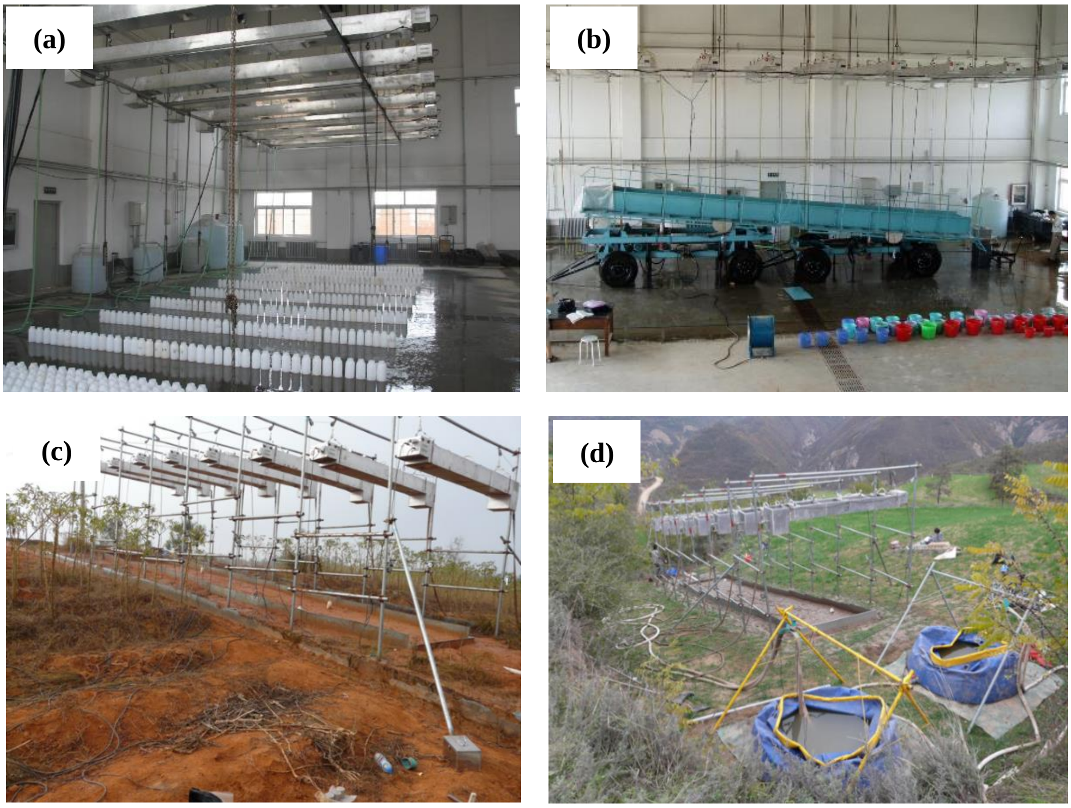

Figure 14 Rainfall simulator indoors (a), Rainfall simulation over an erosion flume (b); Rainfall simulator set outdoors on a slope (c); Rainfall simulator outdoors with water supply (d).

2) Isotopic fingerprint (tracers)

The most commonly used tracer in soil erosion measurement is the radioactive isotope, caesium-137 (^{137}Cs). Caesium-137 was produced in the fall-out of atmospheric testing of nuclear weapons from the 1950s to 1970s. It was distributed globally in the stratosphere and deposited on the earths' surface in the rainfall. Regionally, the amount deposited varies with the amount of rain, but, within small areas, the deposition is reasonably uniform. The isotope is strongly and quickly adsorbed to clay particles within the soil. By analyzing the isotope content of soil cores collected on a grid system varying in density from 10 * 10 to 20* 20 cm, the spatial pattern of isotope loading is established. Figure 15 shows a typical situation (Walling and Quine, 1990). In the pasture at the top of the slope, the isotope is concentrated at the surface; its presence in small amounts at depths is the result of earthworm activity in the soil. On the arable site, the isotope is more uniformly distributed with depth as a result of disturbance of the soil by ploughing. The decline in isotope loading by about 40 percent on the steeper slope is a result of erosion. At the bottom of the slope, there is an increase in loading due to deposition of material. Since the deposition has been active for some years, some of the isotope lies below the present plough depth. Spatial variations in isotope loading in comparison with those at a reference site, usually in either woodland or grassland, have been interpreted successfully, in many parts of the world, as indicating the patterns of erosion and deposition (Ritchie and Ritchie, 2008). When comparing the results with those from erosion plots, it should be noted that they reflect the sum of all the processes by which soil can be redistributed over a field or a hillside, and not just the outcome of interrill and rill erosion that erosion plots often represent (Morgan, 2005).

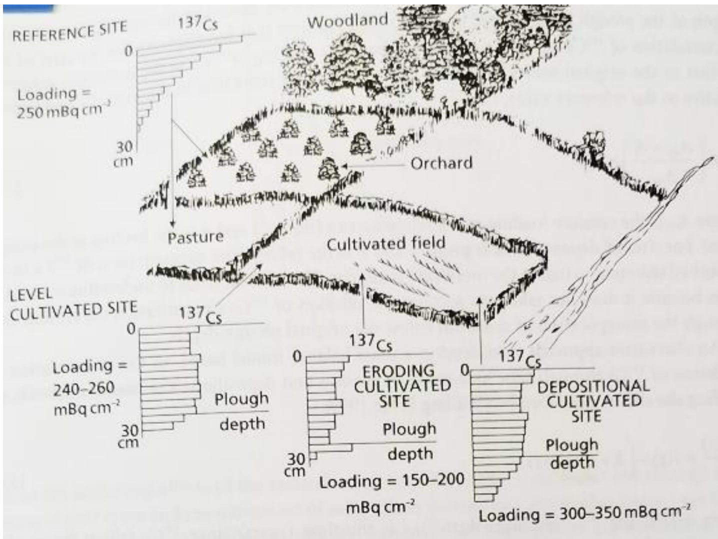

Figure 15 Schematic representation of the effect of erosion and deposition upon the loading and profile distribution of ^{137}Cs (Morgan, 2005).

Since the half-life of the ^{137}Cs is about 30 years, this method provides qualitative information on the patterns of soil erosion and deposition in the landscape over a period of 30-50 years. Similarly, where it is possible to identify separately the fallout from the accident at the Chernobyl nuclear power station in 1986, the method can be used to determine erosion rates over the past 15 years (Golosov, 2003). The potential tracers with shorter half-lives than ^{137}Cs is being investigated to see if they can be used to determine erosion rates over shorter periods. The most promising are unsupported lead-210 (^{210}Pb) and beryllium-7 (^{7}Be) (Morgan, 2005; Walling and He, 1999).

3. How to measure wind erosion?

Unlike water erosion, wind erosion has some unique challenges: 1) wind direction is always changing and highly unpredictable; 2) wind velocities have great vertical variation from the ground to the above; 3) difficult to identify the amount of eroded dust blown in vs. out of the target area.

The techniques for measuring wind erosion are less well established than those for monitoring water erosion. The problem is to design an aerodynamically sound trap to catch soil particles while allowing the air to pass freely through the device. The build-up of back pressure causes resistance to the wind that is deflected from the traps. By careful adjustment of the ratios between the sizes of inlet, outlet and collecting basins, a satisfactory trap can be produced. An example is the Bagnold catcher, consisting of a series of boxes placed on above the other so as to catch all the particles moving through a unit width of air flow at different heights. The disadvantage of the Bagnold catcher is that it cannot be reoriented as wind direction changes. Devices such as the Big Spring Number Eight sampler (Fryear, 1986) and the Wilson and Cooke bottle sampler (Sterk and Raats, 1996) overcome this by being mounted at different heights on a mast to which a wind vane is attached, allowing the whole apparatus to rotate so that the capture tubes always face the wind (Figure 16). These catchers have efficiencies between 75 and 100 percent, depending on the size of particles being carried in the wind (Goossens et al., 2000). The material caught in the traps is collected and weighed after each period of observation. A trap was developed by Janssen and Tetzlaff (1991) where the wind-blown material falls from the collector on to a try mounted on top of a balance. The weight of the material is recorded automatically, thereby giving a continuous record of particle movement throughout a storm. An alternative automatically recording sensor, the saltiphone (Spaan and van den Abeele, 1991) uses a microphone to record the impacts of saltating particles. The main disadvantage of the saltiphone is that it does not collect the material, so its particle size distribution cannot be determined (Morgan, 2005).

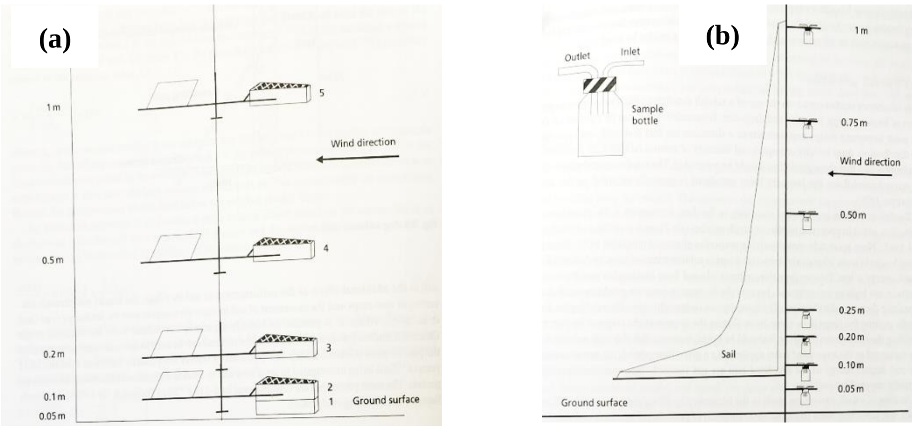

Figure 16 Big Spring Number Eight sampler (a); Wilson and Cooke bottle sampler (b).

A particular problem of wind erosion measurements is to determine the number of samplers required and their best location. Fryear (1986) recommended placing sampling masts, each with a cluster of traps at different heights, in a radical pattern from the center of a field, whereas Sterk and Stein (1997) set up the masts on a grid system. Recent studies have shown that grid and random sampling tend respectively to overestimate and underestimate sediment transport. Better results are obtained with a nested sampling scheme based on placing a parallelogram over the area and locating masts at regular 500-m intervals along each side. Ten from each of these masts, a compass bearing is selected randomly between 0 and 360 and further masts are located along this bearing at 200, 500 and 1000 intervals. It is clear from these studies that a large number of sample points is needed to obtain reliable data (Morgan, 2005).

To overcome these limitations, Baoyuan Liu developed a novel Wind Erosion Measurement Circle (WEMC) (Figure 17). Unlike the conventional rectangular field or rotating samplers, the WEMC is designed as a circle, evenly partitioned by eight clusters, each installing 4 or 6 pairs of directional sediment samplers at different heights. For each pair of the sediment samplers, they always face two opposite directions perpendicular to the tangent, i.e., one inward the circle center to collect sediment leaving the field and the other outward to sample sediment coming in. With such design, the WEMC is not restricted to predominant wind direction or non-erodible boundaries. It can monitor wind erosion for field of any size during a single erosion event or over several consecutive wind events. By applying the WEMC in a corn field for three years in Inner Mongolia, China, it managed to measure wind erosion rates of 2.75, 2.13 and 1.02 t ha^{-1} for 2012, 2013 and 2014. With such virtually comparable wind erosion rate with that determined by ^{137}Cs in nearby field, it clearly demonstrates the effectiveness of the WEMC to reliably capture on-site soil erosion and/or deposition by wind. Therefore, the WEMC has the potential to serve as a standard protocol for on-site wind erosion investigations and model parameterization (Liu, In preparation).

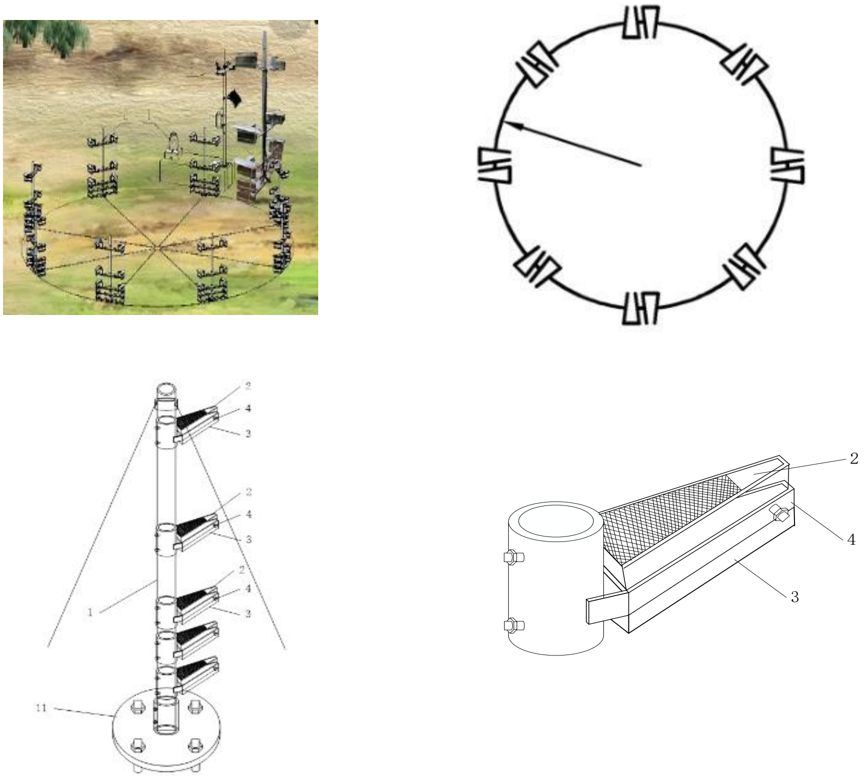

Figure 17 Wind Erosion Measurement Circle and its components.

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