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Jaana Uusi-Kämppä

Natural Resources Institute Finland, Finland



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Quantifying and Managing Soil Erosion on Cropland

Jaana Uusi-Kämpä

Water Quality Impacts, Natural Resources

Natural Resources Institute Finland (Luke)

Tietotie 4, FI-31600 Jokioinen, Finland

KEY TERMS

Detachment

Water erosion

Universal Soil Loss Equation

Transport

Wind erosion

Measurement

Deposition

Tillage erosion

Monitoring

Variables

θ = angle of slope

λ = slope length

a = organic matter content

A = computed average annual soil loss from sheet and rill erosion

b = soil structure code

c = soil profile permeability class

C = crop management factor

K = soil erodibility factor

LS = topographic factor

m = exponent that is a function of slope steepness

M = particle size parameter

P = conservation practice factor

R = rainfall erosivity factor

Introduction

Soil is a major natural resource in food production and therefore it is important to take care of soil in a sustainable manner. In cropland areas, topsoil is degraded by depleting available nutrients and by the removal of soil material from the soil surface via erosion caused by water or wind. Erosion usually occurs more rapidly when the soil is disturbed by human activity or during extreme weather conditions such as high precipitation or drought. Soil loss from a field decreases soil fertility and hence crop yield because of depletion of nutrients, reduction in soil organic carbon, and weakening of soil physical properties (Zhang and Wang, 2006). Recent global estimates suggest that soil erosion removes between 36 and 75 billion tonnes of fertile soil every year (Borelli et al., 2017; Fulajtar et al., 2017) causing adverse impacts to agricultural land and the environment.

In addition to the loss of fertile soil from cropland, erosion processes cause burying of crops and many environmental problems, such as siltation and pollution of receiving watercourses and degradation of air quality. Agrichemicals such as phosphorus and some pesticides adsorbed to eroded soil particles may be transported from croplands. In receiving water bodies, the chemicals may desorb and cause algal blooms or damage the local ecosystems. Due to the many harmful effects caused by soil erosion, it is important to understand erosion processes and how to monitor and prevent them, as well as how to reduce harmful environmental impacts both in the source and impacted (or target) areas. These topics are explored in more detail in this chapter.

Outcomes

After reading this chapter, you should be able to

- Define soil erosion and explain erosion mechanics and transport mechanisms
- Describe measurement and monitoring methods for quantifying erosion
- Explain and apply the Universal Soil Loss Equation (USLE) to estimate soil loss by water
- Calculate average annual soil loss and the effect of different tillage practices on erosion rates

Concepts

What is Soil Erosion?

Soil erosion is a natural geomorphological process by which surface soil is loosened and carried away by an erosive agent such as water or wind. Other agents, such as freezing and thawing, gravity, tillage, and biological activity cause soil movement. Human activity has accelerated erosion for many years, with changes in land use making soil prone to accelerated erosion so that loss is more rapid than replenishment. Tillage, and especially plowing, generally keeps the soil surface bare during winter. Bare soil is prone to erosion, whereas permanent grass or winter plant cover (i.e., cover crop or stubble) on the soil surface protects

soils from erosion. Soil erosion is a local, national, and global problem. In the future, erosion processes may be intensified due to the increase in extreme weather events predicted with climate change. New erosion areas also appear due to deforestation, clearing land for cultivation, and global warming.

Soil Erosion Processes

The process of soil erosion consists of three different parts: detachment, transport, and deposition. First, soil particles are *detached* by the energy of falling raindrops, running water, or wind. Soil particles with the least cohesion are easiest to be loosened. The detached soil particles are then *transported* by surface runoff (also known as overland flow) or wind. Finally, the soil particles start to settle out, or deposit, when the velocity of overland flow or wind and sediment transport capacity decrease. *Deposited* particles are called sediment. Heavier particles, such as gravel and sand, deposit first, whereas fine silt and clay particles can generally be carried for a longer distance and time before deposition. Although particles of fine sand are more easily detached than those of a clay soil, clay particles are more easily transported than the sand particles in water (Hudson, 1971).

In addition to the energy of water or wind used in both detachment and transport of soil particles, gravity may impact erosion either directly, i.e., soil moving downhill without water (e.g., slump mass-movement), or indirectly (e.g., pulling rain to the Earth or drawing floodwaters downward). Bioturbation, which is reworking of soils and sediments by animals or plants, may also play an important role in sediment transport. For example, uprooted trees, invertebrates living underground and moving through the soil (e.g., earthworms), and many mammals burrowing into soil (e.g., moles) can cause soil transport downslope (Gabet et al., 2003).

In some other erosion processes, cycles of freezing and thawing or wetting and drying of clay soils weaken or break down soil aggregates and make the soil more susceptible to erosion. In boreal areas (i.e., northern areas with long winters and short, cool to mild summers), soil erosion may be high during snowmelt periods as a result of soils saturated by water, limited vegetation cover, and high overland flow (Puustinen et al., 2007). Soil erodibility is high in recently thawed soils, since high water content decreases the cohesive strength of soil aggregates (Van Klaveren and McCool, 1998).

Tillage Erosion

Soil erosion caused by tillage has also become more important with the development of mechanized agriculture, while soil erosion caused by water and wind has moved the Earth for millions of years. Tillage erosion has intensified with increased tillage speed, depth, and size of tillage tools, and with the tillage of steeper and more undulating lands (Lindstrom et al., 2001). The amount of soil moved by tillage can exceed that moved by interrill and rill erosion (Lindstrom et al., 2001). In agricultural areas, tillage is the main contributor to accelerated erosion rates. In certain areas, e.g., the U.S. and Belgium, tillage erosion has

created soil banks of several meters high near field borders (Lindstrom et al., 2001). The net soil movement by tillage is generally presented as units of volume, mass, or depth per unit of tillage width (e.g., liter m⁻¹, kg m⁻¹, or cm m⁻¹, respectively).

Types of Soil Erosion Caused by Water on Cropland

Soil erosion caused by water can be classified into several forms including splash, sheet, interrill, rill, gully and bank (Toy et al., 2002). *Splash* erosion is caused by raindrop impact (Fernández-Raga et al., 2017). Small soil particles are broken off of the aggregate material by the energy of falling drops and are splashed into the air (figure 1). Particles may deposit on the soil surface nearby or on flowing water.

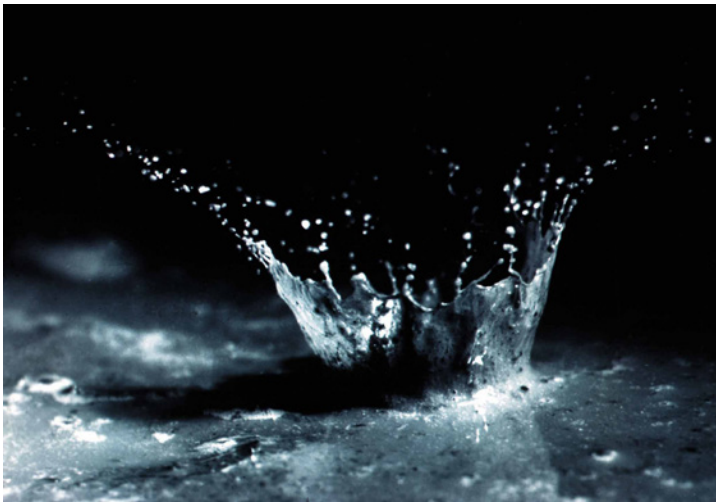


Figure 1. Splash erosion. (Photo courtesy of USDA Natural Resources Conservation Service.)



Figure 2. Gully erosion. (Photo courtesy of USDA Natural Resources Conservation Service.)

Sheet erosion occurs when a thin layer of soil is evenly removed from a large area by raindrop splash and runoff water moving as a thin layer of overland flow. It occurs generally on uniform slopes. Sheet erosion is assumed to be the first phase of the erosion process, and the soil losses are assumed to be rather small (Toy et al., 2002).

Rills are small channels, less than 5 cm deep. They exist when overland flow (or surface runoff) begins to concentrate in several small rivulets of water on the soil surface. Detachment of soil particles is caused by surface runoff (Toy et al., 2002). In general, if a small channel can be obliterated with normal farming operations, it is a rill rather than a channel. After obliteration, rills tend to form in a new location.

The areas between rills are called interrill areas, and the erosion there is defined as *interrill erosion* (Toy et al., 2002). Interrill erosion is a type of sheet erosion because it is uniform over the interrill area. Detachment occurs by raindrop impact, and both surface runoff and detached soil particles tend to flow into adjacent rills.

Gullies are large, wide channels that are carved by running water (figure 2). Ephemeral gullies may occur on croplands and they are able to be filled with soil during tillage operations (Toy et al., 2002). The macrotopography of the surface allows the formation of ephemeral gullies after refilling by tillage. Gullies may sometimes be large enough to prevent soil cultivation. These gullies are called permanent, or classic, gullies. This kind of gully erosion causes severe damage to a field and produces high sediment loads to water.

Bank erosion is direct removal of soil particles from a streambank by flowing water. Bank erosion is the progressive undercutting, scouring and slumping of the sides of natural stream channels and constructed drainage channels (OMAFRA, 2012b).

Types of Wind Erosion

Suspension, saltation, and surface creep are three types of soil movement during wind erosion (figure 3). The dominant manner of erosion depends principally on soil type and particle size. Pure sand moves by surface creep and saltation. Soils with high clay content move under saltation. The sediment moved by creep and saltation may deposit very near the source area, along a fence, in a nearby ditch, or a field (Toy et al., 2002). In suspension, fine particles (diameter less than 0.1 mm) are moved into the atmosphere by strong winds or through impact with other particles. They can be carried extremely long distances before returning to earth via rainfall or when winds subside. In saltation, bouncing soil particles (diameter 0.1–0.5 mm) move near the soil surface. A major fraction of soil moved by wind is through the saltation process. In surface creep, large soil particles (diameter 0.5–1 mm), which are too heavy to be lifted into the air, roll and slide along the soil surface. Particles can be trapped by a furrow or a vegetated area.

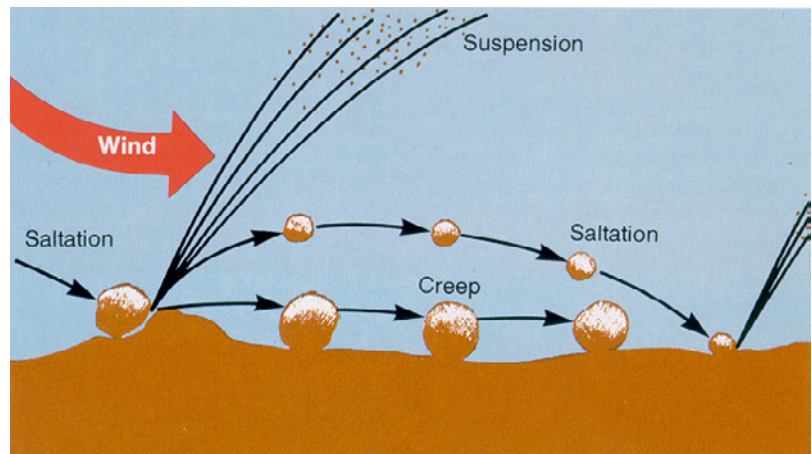


Figure 3. Wind erosion process (USDA ARS, 2020).

Factors Influencing Water and Wind Erosion

Soil erosion is affected by several factors such as climate, rainfall, runoff, slope, topography, wind speed and direction, soil characteristics, soil cover like vegetation or mulch, and farming techniques. For example, in arid climates with steep slopes without good plant cover, during heavy rains the soil erosion is much higher than in level fields with robust plant cover in a mild climate. As another example, soils with high organic matter are naturally more cohesive and, thus, less susceptible to detachment than soils with low organic matter.

Water erosion occurs in areas where rainfall intensity, duration, and frequency are high enough to cause runoff. Wind erosion is most common in arid and semi-arid areas where dry and windy conditions occur. When rainfall water exceeds infiltration (i.e., permeation of water into soil by filtration) into the soil surface, runoff starts to occur. Infiltration capacity depends on soil type. For example, water infiltrates more rapidly into sandy soils than into clay soils; however, water infiltration can be improved in clay-textured soil by aggregate formation. The aggregates, consisting of fine sand, silt, and clay, are typically formed together with a mixed adhesive including organic matter,

clays, iron (Fe) and aluminum (Al) oxides, and lime. At first, rainwater runoff has an impact on light materials (i.e. silt, organic matter, and fine sand particles) in soil, whereas during heavy rainfalls, larger particles are also carried by runoff water. Topography (i.e., slope length and gradient) is also an important factor for water erosion, with longer or steeper slopes being associated with greater erosion rates.

Soil surfaces covered by dense vegetation or mulches are less prone to water erosion due to their protection against the erosive power of raindrops and runoff water. Plants also use water, and their roots bind soil particles. Wind erosion can be counteracted by vegetation, which provides shelter from wind, intercepts wind-borne sediment, and keeps the soil surface moist.

Mechanical disturbance (e.g., soil tillage) buries vegetation or residues that would ordinarily serve as protection from erosion. Anthropogenic, i.e., human-induced, influences, such as changes in land management (animal production vs. crop production) and crop pattern (crop rotation vs. monoculture), use of heavier agricultural machinery, and soil compaction, increase the water and wind erosion potential of soils. Reduced tillage and no-till practices on croplands have been successful in reducing erosion. Globally, intensive deforestation causes soil erosion in new agricultural areas, increasing the net erosion rate.

Estimation and Modeling of Soil Erosion

The average annual erosion rate can be estimated using mathematical models. One of the most widely used models for estimating soil loss by water erosion is the Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978), and its update the Revised Universal Soil Loss Equation (RUSLE) or Modified Universal Soil Equation (MUSLE). According to the USLE, the major factors affecting erosion are local climate, soil, topography (length and steepness of cropland), cover management, and conservation practices.

The standard erosion plot is 22.13 m long and 4.05 m wide, with a uniform 9% slope in continuous fallow, tilled up and down the slope (Wischmeier and Smith, 1978), and is the experimental basis for the development of the empirical USLE model. The soil loss is evaluated as follows by the USLE:

$$A = R K L S C P \quad (1)$$

where A = computed average annual soil loss ($\text{Mg ha}^{-1} \text{ yr}^{-1}$) from sheet and rill erosion

R = rainfall erosivity factor ($\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$)

K = soil erodibility factor ($\text{Mg ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$)

LS = topographic factor (combines the slope length and the steepness factors L and S) (dimensionless)

C = crop management factor (dimensionless, ranging between 0 and 1)

P = conservation practice factor (dimensionless, ranging between 0 and 1; the high value, 1, is assigned to areas with no conservation practices)

Each value on the right can be estimated from figures or tables. To minimize soil loss (A), any one value on the right needs to decrease. The units of R and K in equation 1 are a result of adapting the USLE to use in SI units. The USLE was derived using customary U.S. units (e.g., tons, inches, acres). With international application of USLE, adoption of SI units was important. Several authors (e.g., Foster et al., 1981) have described approaches for use of the USLE in SI units.

Rainfall Erosivity Factor (R)

The rainfall and runoff factor (R), is related to the energy intensity of annual rainfall, plus a factor for runoff from snowmelt or applied water (irrigation) (Wischmeier and Smith, 1978). Rainfall erosivity defines the potential ability of the rain to produce erosion. Erosivity depends solely on rainfall properties (e.g., drop velocity, drop diameter, rainfall rate and duration) and frequency of a rainstorm. The greatest erosion occurs when rainfall with high intensity beats a bare soil surface without any plant cover. Plants or stubble are good cover against rainfall erosivity.

The National Soil Erosion Research Laboratory has presented a figure of the aerial erosion index for different areas of the U.S. varying from <200 to 10,000 (Foster et al., 1981). Several regional and global rainfall erosivity maps (e.g., ESDAC, 2017) are available. Erosivity also varies according to the season (Toy et al., 2002), being highest during winter and early spring in boreal areas.

Soil Erodibility Factor (K)

The soil erodibility factor is the soil loss rate per erosion index unit for a specified soil as measured on a standard erosion plot. It is based on the soil texture, soil structure, percent organic matter, and profile-permeability class (Wischmeier and Smith, 1978; Foster et al., 1981) and reflects the susceptibility of a soil type to erosion. Soils high in clay content have low K factor values because the clay soils are highly resistant to detachment of soil particles. In general, there is little control over the K factor since it is largely influenced by soil genesis. However, some management choices can result in small changes to the K factor. For example, by increasing the percent of organic carbon in soil, the K factor can be decreased, since organic matter increases soil cohesion.

The K factor in SI units ($\text{Mg ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$) can be estimated using a regression equation that considers soil texture, organic matter content, structure, and permeability (Mohtar, n.d.):

$$K = 2.8 \times 10^{-7} \times M^{1.14} (12 - a) + 4.3 \times 10^{-3} (b - 2) + 3.3 \times 10^{-3} (c - 3) \quad (2)$$

where M = particle size parameter = (% silt + % very fine sand) \times (100 - % clay)

a = organic matter content (%)

b = soil structure code (very fine granular = 1; fine granular = 2; medium or coarse granular = 3; blocky, platy, or massive = 4)

c = soil profile permeability class (rapid = 1; moderate to rapid = 2; moderate = 3; slow to moderate = 4; slow = 5; very slow = 6)

The K factor can also be read from nomographs, e.g., Foster et al. (1981) provided a nomograph in SI units.

In reality, soil erodibility is more complicated than equation 2 suggests. How erodible a soil is depends not only on the physical characteristics of the soil but also its treatment, which effects how cohesive the soil aggregates are. Some variations of the USLE, such as the Second Revised USLE (RUSLE2) use a more complicated and dynamic K factor to account for management effects.

Topographic Factor (LS)

The topographic factor (called also slope length factor) describes the combined effect of slope length and slope gradient. This factor represents a ratio of soil loss under given conditions to that on the standard plot with 9% slope. Thus, $LS = 1$ for slope steepness of 9% and slope length of 22.13 m (Wischmeier and Smith, 1978); $LS > 1$ for steeper, longer slopes than that, and < 1 for gentler, shorter slopes. For example, LS factor values for a 61 m long slope with steepness of 5%, 10%, 14%, and 20% are 0.758, 1.94, 3.25, and 5.77, respectively. The LS factors for 122 m and 244 m long slopes with constant steepness of 10% are 2.74 and 3.87, respectively. The steeper and longer the slope, the higher the erosion risk. The LS factor can be determined from a chart or tables in standard references (Wischmeier and Smith, 1978), or from equations where both slope length and steepness have been taken into consideration, e.g., Wischmeier and Smith (1978):

$$LS = \left(\frac{\lambda}{22.13} \right)^m (65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065) \quad (3)$$

where λ = slope length (m)

θ = angle of slope

$m = 0.5$ if the slope is 5% or more, 0.4 on slopes of 3.5 to 4.5%, 0.3 on slopes of 1 to 3%, and 0.2 on uniform gradients of less than 1%

Equations such as equation 3 were derived for specific conditions, so care must be taken in using the appropriate equation for the given situation. These equations can be found in various USLE references. There is limited ability to change the LS factor, except for, notably, breaking a long slope into shorter slope lengths through the installation of terraces.

Cover Management Factor (C)

The cover management factor is a ratio that compares the soil loss from an area with specified cover and management to that from an identical area in tilled continuous fallow. The value of C on a certain field is determined by several variables, such as crop canopy, residue mulch, incorporated residues, tillage, and land use residuals (Wischmeier and Smith, 1978).

The factor may roughly be determined by selecting the cover type and tillage method that corresponds to the field and then multiplying these factors together (OMAFRA, 2012a). The height and density of a canopy reduces the rainfall energy. Residue mulch near the soil surface is more effective to reduce soil loss than equivalent percentages of canopy cover (Wischmeier and Smith, 1978).

For example, incorporating plant residue at the soil surface by shallow tillage offers a greater residual effect than moldboard plowing. The *C* factor for crop type varies from 0.02 (hay and pasture) to 0.40 (grain corn). The *C* factor for tillage method varies from 0.25 (no-till or zone tillage) to 1.0 (fall plow). However, local investigation of the *C* factor is highly recommended because of varying cultivation practices, and because of the interaction of the timing of crop cover development and the timing of rainfall energy, which varies from place to place. Selection of crops and tillage systems can have a huge impact on the *C* factor.

Conservation Practice Factor (P)

The conservation (also support practice or erosion control) factor reflects the effects of various practices that will reduce the amount and rate of water runoff and, thus, reduce the erosion rate (Wischmeier and Smith, 1978). The most commonly used supporting cropland practices are cross-slope cultivation, contour farming, and strip cropping. The highest *P* factor value of 1 is given in the case when no influences from conservation practices are considered. The value of 1 is also given to “up and down slopes,” while “strip cropping, contour” gets the lowest value of 0.25 in the factsheet of Ministry of Agriculture, Food and Rural Affairs Ontario (OMAFRA, 2012a).

Measurement and Monitoring

Scientific research and erosion measurements are needed to understand erosion processes. Erosion is measured for three principal reasons (1) erosion inventories, (2) scientific erosion research, and (3) development and evaluation of erosion control practices (Toy et al., 2002). Measurements are also needed for the development of erosion prediction technology and implementation of conservation resources and development of conservation regulations, policies, and programs (Stroosnijder, 2005). Erosion measurements are used for development, calibration, and validation of methods of erosion prediction.

Temporal and Spatial Measurements

Erosion measurements are made at various temporal and spatial scales (Toy et al., 2002). For example, sampling duration can vary from a single rainstorm or windstorm to several years.

Spatially, water erosion measurements can range from interrill and rill sediment sources on hillslope or experimental plots to sediment discharge from watersheds. The presence of rills gives evidence of the possible erosion problems on the field. Sediment discharge from watersheds is used in reservoir design. Wind erosion measurements range also from small plots to agricultural fields and to entire regions.

Erosion Inventories

In planning erosion inventory measurements, the following issues should be included (Toy et al., 2002): selection of measurement site(s), measurement frequency and duration at the sites, and suitable measurement techniques. The

selection of sites is made according to a sampling strategy. The measurement duration should be long enough to capture the temporal variability of erosion processes. The measurement technique is selected according to erosion type and study question.

How to Measure?

Erosion research is possible in the field (outdoor) or in the laboratory (Toy et al., 2002). Stroosnijder (2005) presents the following five fundamental ways to measure erosion: (1) sediment collection from erosion plots and watersheds, (2) change in surface elevation, (3) change in channel cross section dimensions, (4) change in weight, and (5) the radionuclide method. Both direct measurements and erosion prediction technology are used in erosion inventories. Commonly used erosion measurement techniques are cheap and fast but not very accurate. More accurate methods are costly and beyond the budget of many projects.

Experimental Fields and Catchments

In outdoor research settings, experimental plots, cropland fields or catchments are in use and runoff may be caused by natural or artificial rainfall. Temporal surface runoff (overland flow movement of water exclusively over the soil surface, down slope, during heavy rain) and subsurface discharge (drainage flow) from these sites can be measured and water sampled for sediment analyses. Sampling can be done automatically according to water volume or time. For indoor studies, soil blocks under a rainfall simulator (e.g., stationary drip-type rainfall simulator) can be used (Uusitalo and Aura, 2005). In both cases, representative water samples are collected for the sediment concentration analyses in the laboratory.

To predict the sediment load for a certain study area and time period, the concentration of analyzed water samples is multiplied by the water volume of the sampling period. Water flow ($L s^{-1}$) can be measured in stream with a flow meter or V-notch weir, and on croplands with tipping buckets. Erosion amount ($kg ha^{-1}$) is estimated by multiplying water flow ($L s^{-1}$) by the time (s) and sediment concentration ($g L^{-1}$) and finally dividing by the size of the study area (ha).

Also, continuously operating sensors for turbidity measurements from water can be used for measuring erosion from a study area. Turbidity is the degree to which water loses transparency due to suspended particles like sediment; the murkier the water, the more turbid it is. Turbidity sensors need good calibration and control water samples to evaluate sediment content. They must also be equipped with an automatic cleaning mechanism.

Change in Surface Elevation (Hillslope Scale)

The change in elevation is based on the principle that erosion and deposition by water or wind change the elevation of the land surface (Toy et al., 2002). The difference between the two measurements indicates the effect of erosion and deposition during that time interval. A lower elevation indicates erosion and higher elevation at the end of time interval indicates deposition.

One approach to measure change in elevation is to implant stakes or pins that remain in place in the soil for the duration of the study. The distance from the

top of the stake or pin to the ground is measured at set time intervals. A decrease in distance corresponds to sedimentation whereas an increase means erosion (Stroosnijder, 2005). By multiplying the change in elevation by the soil bulk density, it is possible to convert the measurement to a mass of soil (Toy et al., 2002). In figure 4, a soil roughness meter is used to measure changes in the surface of soil. The soil roughness meter has a set of pins that sit on the surface, so that soil surface position measurements can be made relative to the top of the structure of the roughness meter. By making repeated measurements at the same location, small changes in the surface elevation can be measured. It may also be used to determine soil erosion in rills.



Figure 4. A soil roughness meter is used to measure changes in the surface of soil. Photo: Risto Seppälä, Natural Resources Institute Finland (Luke).

Change in Channel Cross Section

Channel erosion can be estimated by measuring cross sections at spaced intervals, repeating this after some time and comparing and determining the change in volume of soil. The measurement can be done either manually or using airborne laser scanners (Stroosnijder, 2005). This technique is also suitable for estimating rill or gully erosion on croplands.

Change in Weight (Collected by Splash Cups and Funnels)

This method is based on the principle that the erosion process removes material from the source area (Toy et al., 2002). Test soil, packed in a cup or funnel placed in the soil, is weighed before and after an erosion event, and loss of weight is the erosion measurement. This technique is used in studies of soil detachment and transport by raindrop force (Stroosnijder, 2005). While affordable, and accurate at a small scale, the results using this method are representative of only a very small area, and may not scale well to the field level.

Radionuclide Method

Environmental radionuclides can be used as tracers to estimate soil erosion rates (Stroosnijder, 2005). A human-induced radionuclide of cesium (Cs^{137}) was released into the atmosphere during nuclear weapon tests in the 1950s and 1960s. It spread to the stratosphere and gradually deposited on the land surface. In studies using this method, an undisturbed reference site, on which no or minimal erosion or sedimentation occurs, is needed (Fulajtar et al., 2017). The Cs^{137} concentration in the study soil is compared to the concentration in the reference site. If the study site contains less Cs^{137} than the reference site, erosion occurs there. If the study site has more Cs^{137} than the reference, sedimentation (deposition of soil particles) has occurred. In radionuclide studies, the time scale is usually much longer than in agronomic or environmental studies (Stroosnijder, 2005).

Wind Erosion Measurements

Wind erosion measurements require different measurement plans and equipment than water erosion measurements (Toy et al., 2002). While water erosion follows topography and water flow paths, windblown sediment cannot be collected at a single point (Stroosnijder, 2005). Soil gains and losses due to wind erosion require a number of measurement points, followed by geostatistical analyses. Since wind blows from various directions during the year and during a storm, sediment samplers must rotate with changing wind directions. Measurements must be made at various heights to determine the vertical distribution of the sediment load (Toy et al., 2002).

Impacts of Soil Erosion In-Field and Downstream

Soil erosion has impacts both on croplands where the erosion process starts (detachment) and in the place where it ends up (deposition, sedimentation) (figure 5).

Impacts in Fields

In fields, fertile top soil material can be lost due to erosion processes. The finest particles from topsoil are generally transported from field areas under convex slopes making the areas less productive. The loss of finest particles reduces further the physical structure and fertility of soils (Hudson, 1971). Removal of fine particles or entire layers of soil or organic matter can weaken the structure and even change the texture, which can in turn affect the water-holding capacity of the soil, making it more susceptible to extreme conditions such as drought (OMAFRA, 2012b). Erosion of fertile topsoil results in lower yields and higher production costs.



Figure 5. Sediment chokes this stream due to many years of erosion on nearby unprotected farmland. (Photo courtesy of USDA Natural Resources Conservation Service.)

Sediment may either increase fertility of soil or impair its productivity on productive land. For example, in Egypt, the fields along the Nile River are very productive due to nutritious sediments from the river water. In some cases, the sediment deposited on croplands may inhibit or delay the emergence of seeds, or bury small seedlings (OMAFRA, 2012b). Dredging of open ditches, sedimentation ponds, and waterways, in which sediment is mechanically removed, is becoming more common. However, it is questionable whether dredged sediment can be recycled back to agricultural fields (Laakso, 2017). The sediment may contain substances that are harmful to crops (herbicides) or decrease soil fertility (e.g., aluminum and iron hydroxides).

Impacts Downstream and in Air

In streams and watercourses, sediment can prevent water flow, fill in water reservoirs, damage fish habitats, and degrade downstream water quality. With an enrichment of nutrients, pesticides, salts, trace elements, pathogens, and toxic substances in soil particles in the field, soil erosion causes contamination of downstream water sources, wetlands, and lakes (OMAFRA, 2012b; Zhang and Wang, 2006). Because of the potential harmful impacts of deposited soil particles in water, the control of soil erosion in the field is important. Siltation of watercourses and water storages decreases the storage capacity of water reservoirs.

In addition, fine particles (<0.1 mm) transported by wind may also cause visibility problems on roads. They may also penetrate into respiratory ducts causing health problems.

Applications

For best results, erosion control should begin at the source area, by preventing detachment of soil particles. One of the most effective ways to prevent erosion is through crop and soil management. Detached particles can be trapped by different tools both on cropped field, field edges, and outside fields.

Decreasing the Effects of Erosivity (R) and Erodibility (K)

Erosivity is rather difficult to decrease since there are no tools to affect rainfall. Soil erodibility can be decreased by increasing soil organic matter in soil, e.g., by adding manure or other carbon sources to soil. Practices that reduce or mitigate loss of soil carbon in cropped land can also decrease erodibility. These methods include managing residue to return carbon to the soil and minimizing tillage to reduce the conversion of soil carbon to carbon dioxide gas. Decreasing soil erosion caused by water on highly erodible soils requires additional methods such as permanent grass cover or zero tillage.

The addition of manure, compost, or organic sludge into soil increases aggregate stability, porosity, and water-holding capacity (Zhang, 2006). Both inorganic (stone, gravel, and sand) and organic mulches (crop residue, straw, hay, leaves, compost, wood chips, and saw dust) are used to absorb the destructive forces of raindrops and wind. All these materials also obstruct overland flow and increase infiltration (Zhang, 2006). Mulch reduces erosion until the seedlings mature to provide their own protective cover. In addition, soils treated with amendments like gypsum or structure lime are more durable against erosion than untreated soils (Zhang, 2006). The effect of these soil amendments lasts for a certain period depending on soil and environmental conditions. To maintain the effect, the amendment must be reapplied at intervals.

Soil moisture can prevent erosion. A moist soil is more stable than a dry one, since the soil water keeps the soil particles together. Soil moisture is higher in untilled soils due to a higher percent of organic carbon and minimal evaporation from the soil covered by plant residues. For example, wind erosion can be controlled by wetting the soil.

Reducing the Effect of Topography

Long slopes can be shortened by establishing terraces, but it is difficult to make steep slopes gentler. Reducing the field width (e.g., by windbreaks) protects cropped land against the effects of wind (figure 6).

Increasing the Effect of Cover and Management

Plants are excellent in the protection of soil. They keep the soil in place with their roots, intercept rainfall, provide cover from wind and runoff, increase water infiltration into soil, increase soil aggregation, and provide surface roughness that reduces the speed of water or air movement across the surface. Dense



Figure 6. Field windbreaks in North Dakota (U.S.) protect the soil against wind erosion. (Photo courtesy of USDA Natural Resources Conservation Service.)



Figure 7. No-till drilling of soybeans into wheat stubble (Louisiana, USA). (Photo courtesy of USDA Natural Resources Conservation Service.)

perennial grasses are the most effective erosion controlling plants.

Soil management techniques that disrupt the soil surface as little as possible are excellent at maintaining soil cover and structure. For example, eliminating tillage (called no-till, e.g., direct drilling) keeps the soil surface covered all year round (figure 7). This method, where seed is placed without any prior soil tillage in the stubble, has become common in many dry growing regions to decrease erosion potential. In winter, the stubble remaining after harvest effectively reduces soil erosion compared to bare fields (e.g., plowed in fall). Reduced, or conservation, tillage is also a better choice than fall plowing that leaves the soil surface uncovered. Tillage decreases the organic matter in soils and, thus, has a negative effect on the aggregate stability of clay soils (Soinne et al., 2016). Tillage also disturbs soil structure and, thus, reduces infiltration capacity.

Controlled grazing causes less erosion than tilled croplands; however, the number of grazing animals must be kept low enough to prevent erosion caused by over-grazing. Crop rotation and use of cover crops also maintain soil fertility and, thus, help control erosion. Cover management affects soil erosion in increasing order: meadows < grass and legume catch crops turned under in spring < residue mulch on soil surface < small grain or vetch on fall-plowed seedbed and turned at a spring planting time < row crop canopy < shallow tillage < moldboard plow < burning / removing residues < short period rough fallow in rotation < continuous fallow.

Increasing the Effect of Support Practices

On steep slopes, erosion can be controlled by support practices like contour tillage (figure 8), strip cropping on contour, and terrace systems (Wischmeier and Smith, 1978). Strip cropping protects against surface runoff on sloping fields and decreases the transport capacity of soil.

Tillage and planting on the contour is generally effective in reducing erosion. Contouring appears to be most effective on slopes in the 3–8% range (Wischmeier and Smith, 1978). On steeper slopes, more intervention is usually needed. Contour strip cropping (figure 9) is a practice in which contoured strips of dense vegetation, e.g., grasses, legumes, or corn with alfalfa hay, are alternated with equal-width strips of row crops (e.g., soybeans, cotton, sugar beets), or small grain (Wischmeier and Smith, 1978). In erodible areas, grass strips usually 2 to 4 m wide are placed at distances of 10 to 20 m (figure 10). They can be placed on critical areas of the field and the main purpose of these strips is to protect the land from soil erosion. Terracing can be combined with contour farming and other conservation practices making them more effective in erosion control (Wischmeier and Smith, 1978).

In terrace farming, plants may be grown on flat areas of terraces built on steep slopes of hills and mountains. Terracing can reduce surface runoff and erosion by slowing rainwater to non-erosive velocity. Every step (terrace) has an outlet which channel water to the next step.

If soil detachment and transport have taken place, the next consideration is to control deposition before the runoff enters a receiving watercourse. Narrow, 1 to 5 m wide, buffer strips under perennial grasses and wider buffer zones under perennial grasses and trees (figure 11) have been established along rivers to prevent sediment transport to watercourses (Haddaway et al., 2018, Uusi-Kämppe et al., 2000). Grassed waterways (figure 10) are established on concentrated water flows in fields to decrease water flow and, thus, decrease the erosion process in a channel.



Figure 8. Contoured field in southwest Iowa, USA. (Photo courtesy of USDA Natural Resources Conservation Service.)



Figure 9. Alternating strips of alfalfa with corn on the contour protects this crop field in northeast Iowa, USA, from soil erosion. (Photo courtesy of USDA Natural Resources Conservation Service.)

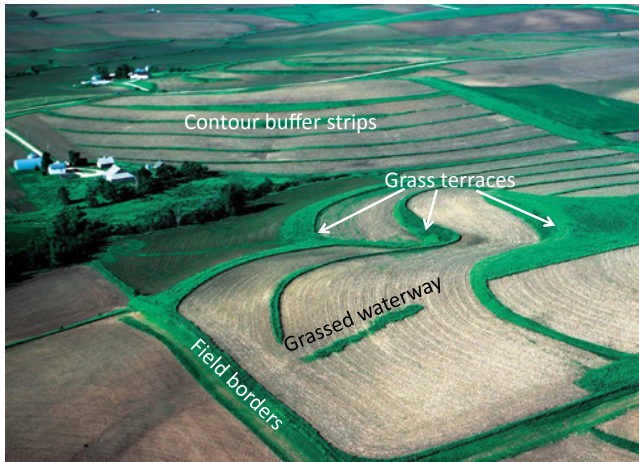


Figure 10. Grass helps protect this western Iowa, USA, cropland with practices including contour buffer strips, field borders, grassed waterways, and grass on terraces. (Photo courtesy of USDA Natural Resources Conservation Service.)



Figure 11. Multiple rows of trees and shrubs, as well as a native grass strip, combine in a riparian buffer to protect Bear Creek, in Iowa, USA. (Photo courtesy of USDA Natural Resources Conservation Service.)

Sediment basins, ponds and wetlands are also used to trap sediment (Uusi-Kämppe et al., 2000). Large particles and aggregates settle over short transport distances, while small clay and silt particles can be carried over long distances in water before their sedimentation.

Country-Specific Perspectives on Soil Erosion

Due to climatic factors (*R*), soil characteristics (*K*), landscape features (*LS*) and cropping practices (*C*), soil erosion varies geographically. Soil erosion by water is highest in agricultural areas with high rainfall intensity (*R* factor). In the U.S., the erosion index is great ($1200\text{--}10,000 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$) in eastern, southern, and central parts where tropical storms and hurricanes occur. In Europe, the *R* factor is highest in the coastal area of the Mediterranean, from 900 to $>1300 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ (Panagos et al., 2015). In addition to climate, changes in cropping systems (*C* factor) influence the amount of erosion.

In northern Europe, the most erodible agricultural areas exist in southeast Norway (soil types are silty clay loams or silty clay), southern and central Sweden, and in southwestern Finland (with clay) due to the *K* factor. In these boreal areas, erosion risk is highest during late fall, winter, and spring due to surface runoff in frozen soil. Soil was previously covered by snow in winter; however, these areas have more frequently been subject to melting and runoff in winter during the last centuries due to climate change (*R* factor).

In the 1900s, global cropland area increased causing a similar reduction in grassland area (*C* factor). In Norway, the change in land use doubled soil erosion by water. In addition, extensive land levelling and putting brooks into pipes increased agricultural area in the same region in the 1970s and led to a two-to-three fold increase in erosion (Lundekvam et al., 2003), because levelling, i.e., creating smooth slopes instead of undulating ones, tended to increase the *LS* factor. Intensive erosion research started in the 1980s and since then Norwegian farmers have received national payments to implement erosion reducing methods, e.g., zero-tillage and growing cover crops in fall (*C* factor), or establishment of grassed waterways, buffer strips, and sedimentation ponds (*P* factor). Also, re-opening of piped brooks

(decrease in L factor), and conversion of fall-tilled fields with high erosion risk into permanent grassland (C factor) have been subsidized.

In Finland, typical soil erosion processes in field are sheet erosion, rill erosion, and tillage erosion. Although the mean arable soil loss rate is low ($460 \text{ kg ha}^{-1} \text{ yr}^{-1}$) according to estimations of the RUSLE2015 model (Lilja et al., 2017), there are areas where the erosion risk is higher than this. These high risk areas, with steep slopes and high percent crop production, exist in south-western parts of the country. In Finland, erosion is mitigated to decrease losses of phosphorus, which can be desorbed from detached soil particles into receiving water bodies where it may cause eutrophication and harmful algal blooms. To decrease soil erosion, some agri-environmental measures are subsidized by the European Union and Finland. For example, fall plowing has been replaced by conservation tillage practices, e.g. no-tillage and direct drilling (C factor) or fields may be left under green cover crops for the winter (C factor). Grass buffer zones, erosion ponds, or wetlands may be installed and maintained between fields and water bodies to trap soil particles rich in phosphorus (P factor).

Examples

Example 1: Calculate average annual soil loss

Problem:

Use the USLE model to calculate the annual soil loss from a Finnish experimental site (slope steepness 6%, length 61 m, $60^{\circ}48'N$ and $23^{\circ}28'E$). Annual rainfall is 660 mm, and erosivity is $311 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ (Lilja et al., 2017). The site is plowed (up and down slope) in the fall and sown with spring wheat. Particle distribution: clay ($<0.002 \text{ mm}$) 30%, silt ($0.002\text{--}0.02 \text{ mm}$) 40%, very fine sand ($0.02\text{--}0.1 \text{ mm}$) 25%, and sand ($>0.1 \text{ mm}$) 5%. Organic matter in the soil is 2.8%. Soil structure is fine granular, and permeability is slow to moderate.

Solution:

Determine the value of each factor in equation 1:

$$A = R K L S C P \quad (1)$$

R = rainfall erosivity factor; given in problem statement = $311 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$

K = soil erodibility factor; calculate using equation 2:

$$K = 2.8 \times 10^{-7} \times M^{1.4} (12 - a) + 4.3 \times 10^{-3} (b - 2) + 3.3 \times 10^{-3} (c - 3) \quad (2)$$

where M = particle size parameter

$$= (\% \text{ silt} + \% \text{ very fine sand}) \times (100 - \% \text{ clay}) = 65\% \times (100 - 30\%) = 4550$$

$$a = \text{organic matter content (\%)} = 2.8$$

$$b = \text{soil structure code} = 2 \text{ (fine granular)}$$

$$c = \text{soil profile permeability class} = 4 \text{ (slow to moderate)}$$

Thus, substituting values in equation 2 yields:

$$K = 0.041 \text{ Mg ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$$

LS = topographic factor; find from a published table, e.g., table 3 (Wischmeier and Smith, 1978) or the following excerpt from Factsheet table 3A (OMAFRA, 2012a):

Slope Length (m)	Slope (%)	LS Factor
61	10	1.95
	8	1.41
	6	0.95
	5	0.76
	4	0.53

For a slope length of 61 m and a slope steepness of 6%, $LS = 0.95$, or calculate LS using equation 3:

$$LS = \left(\frac{\lambda}{22.13} \right)^m (65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065) \quad (3)$$

$$LS = \left(\frac{61}{22.13} \right)^{0.5} (65.41 \sin^2 (6\%) + 4.56 \sin(6\%) + 0.065) = 0.95$$

C = crop management factor = 0.35 for cereals

P = conservation practice factor = 1.0 for fall plowing up and down slope (OMAFRA, 2012a).

Substitute the values for each factor in equation 1:

$$A = R K L S C P \quad (1)$$

$$= 311 \times 0.041 \times 0.95 \times 0.35 \times 1 \text{ Mg ha}^{-1} \text{ yr}^{-1} = 4.24 \text{ Mg ha}^{-1} \text{ yr}^{-1}$$

Example 2: Effect of different tillage practices on erosion rates

Problem:

Use the USLE model to evaluate the change in erosion rate in the field runoff of the previous example when fall plowing (up and down slope) is changed (a) to spring plowing (cross slope) or (b) to no-till (up and down slope).

Solution:

(a) Using equation 1 with:

$$R = 311 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$$

$$K = 0.041 \text{ Mg ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$$

$$LS = 0.95$$

$$C = 0.35 \text{ (cereals)} \times 0.9 \text{ (spring plow)} = 0.315$$

$$P = 0.75 \text{ (cross slope)}$$

$$A = R K L S C P = 2.86 \text{ Mg ha}^{-1} \text{ yr}^{-1}$$

The erosion rate is 32% less due to cross slope plowing in spring compared to up and down plowing in fall.

(b) Using equation 1 with:

$$R = 311 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$$

$$K = 0.041 \text{ Mg ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$$

$$LS = 0.95$$

$$C = 0.35 \text{ (cereals)} \times 0.25 \text{ (no-till)} = 0.0875$$

$$P = 1 \text{ (up and down slope)}$$

$$A = R K L S C P = 1.06 \text{ Mg ha}^{-1} \text{ yr}^{-1}$$

The erosion rate is 75% less due to direct drilling compared to up and down plowing in fall.

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