Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 154, Pages 48-59, April 2015

Soil Erosion in Humid Regions: A Review

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Abstract: Soil erosion has significant implications for land productivity and surface water quality, as sediment is the leading water pollutant worldwide. Here, erosion processes are defined. The dominant factors influencing soil erosion in humid areas are reviewed, with an emphasis on the roles of precipitation, soil moisture, soil porosity, slope steepness and length, vegetation, and soil organisms. Erosion dynamics in forested watersheds are the focus with some examples from agricultural watersheds included as well. Lastly, best management practices for controlling surface erosion are discussed.

Keywords: *best management practices, erosion control, forest, precipitation, sediment, surface erosion, water quality, watershed management*

Erosion is a critical process for land and watershed managers to understand, as sediment is the world's leading surface water pollutant. Excessive erosion results in significant topsoil losses, leading to declines in agricultural productivity. Reservoir lifespans can be shortened due to excessive sedimentation behind dams. Sediment can carry bound nutrients such as phosphorus, which contribute to the eutrophication of freshwater resources and coastal estuaries (Rabalais et al. 2010). Stream and river habitat for fish and macroinvertebrates can become degraded when benthic habitats are covered with sediment, resulting in declines in freshwater biodiversity (Bilotta and Brazier 2008).

Process of Erosion

Erosion is a natural process, where energy provided by water, wind, and gravity drives the detachment, transport, and deposition of soil particles. **Detachment** occurs when the forces holding a soil particle in place are overcome by the forces of raindrop impact, moving water, or wind (Joy et al. 2002; Rose 1960). A portion of the energy from raindrop impact is first spent to deform **peds** (i.e., aggregrates of soil particles) and detach soil particles from the surface. Remaining energy activates the second step of the erosion process, particle **transport** (Rose 1960; Savat and Poesen 1981). **Deposition** is the third and final step in the erosion process and occurs simultaneously with the first two steps (Huang et al. 1999). When the sediment load of moving water is greater than its transport capacity, deposition occurs (Foster and Meyer 1972). Recently-deposited soil is more vulnerable for re-detachment and transport than residual soil because the original bonding forces have been broken (Hairsine et al. 1992; Woo et al. 1997). However, a layer of recently deposited loose soil can help prevent detachment of underlying soil (Kinnell 2005). Individual soil particles can be detached, transported, and deposited several times during a single storm event (Hairsine et al. 1992).

Physics of Erosion

This review focuses on erosion by water, as it is the dominant form of erosion in humid climates. Erosion by water is categorized by the type of runoff or overland flow across the earth's surface. During precipitation events, overland flow is generated when precipitation exceeds the infiltration capacity of the soil (Horton 1933) or when precipitation falls on saturated soils with a high water table (Dunne 1983). The resulting overland flow begins

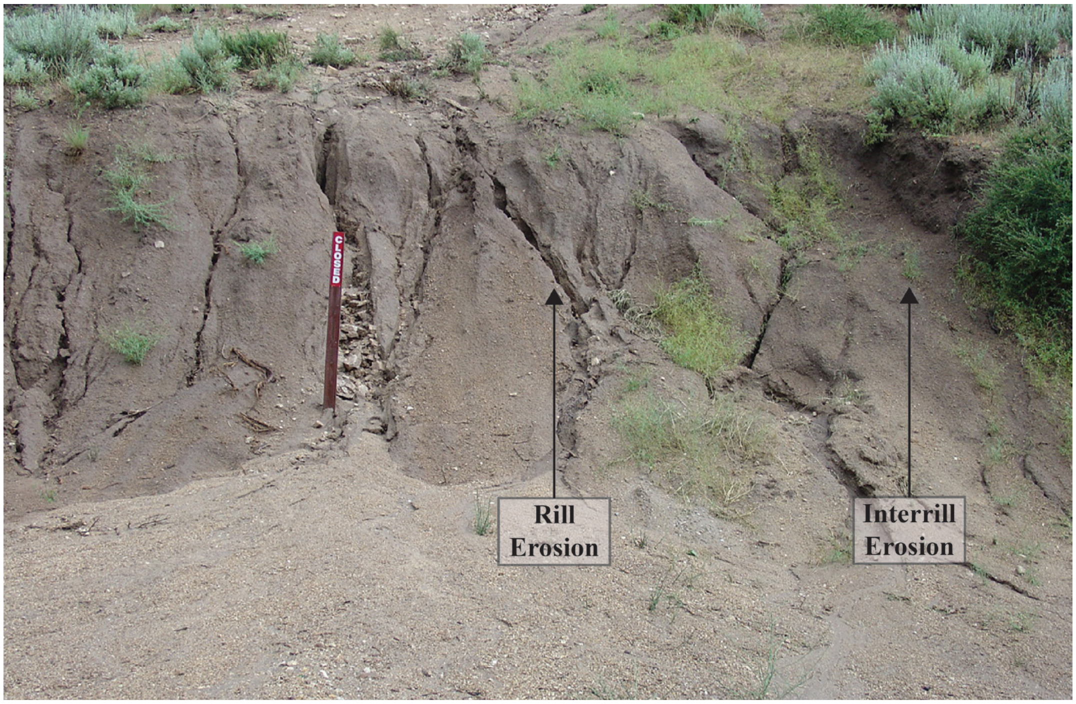

Figure 1. Rill and interrill erosion on a cutslope portion of a road prism in the western United States. Note the multiple rills or small eroded channels. The areas between the rills experience interrill erosion (Photo credit: USDA Forest Service).

as **sheetflow** (i.e. shallow, dispersed runoff). The energy associated with raindrop impact and sheetflow can detach and transport soil particles and is termed **interrill erosion** (Meyer 1981) (Figure 1). Of the two forces, raindrop impact supplies most of the kinetic energy needed for interrill erosion to occur (Rose 1960; Salles and Poesen 2000,; Kinnell 2005). The kinetic energy of the raindrop is proportional to its mass and its velocity squared; bigger drops have more mass and greater terminal velocity, and thus, more energy (Laws 1941). The effect of the energy depends on soil characteristics and conditions. Some energy is used to wet, deform, and detach soil particles, while the remaining energy is used to move the soil vertically and laterally (Rose 1960; Savat and Poesson 1981). At the start of a rainfall event on dry soil, raindrops can deform the soil surface. As the soil wets beyond its plastic limit (i.e., the moisture content of soil when it first becomes malleable), its shear strength decreases, rendering soil particles more vulnerable to detachment and transport (Bryan 2000).

Since the earth's surface is irregular and not perfectly smooth, **sheetflow** quickly concentrates into micro-channels, or **rills**, becoming **concentrated overland flow** (Rauws and Govers 1988; Torri et al. 1987) (Figure 1). **Rill erosion** occurs at the point at which flowing water has enough energy to dislodge soil particles from the surface and begin incision. When rill erosion first occurs, erosion rates can increase dramatically (Römkens et al. 1997; Bryan 1990). Rills are the primary conveyor of eroded soil from the landscape and are capable of long distance transport (Kinnell 2005). Interrill and rill erosion can occur simultaneously since raindrop impact continues to occur between established and developing rills (Bryan 2000). If rill erosion progresses, gullies can form and create larger and more permanent channels (Figure 2) (Sidorchuk 1999). As runoff volume increases, more energy is available for additional erosion (Huang et al. 1999).

Physical and Hydraulic Soil Properties Influencing Erosion

Physical and hydraulic soil properties are the most important factors that determine soil

Figure 2. An active gully below a road drain point in the western United States (Photo credit: USDA Forest Service).

erodibility (Pierzynski et al. 2005). These soil properties include **antecedent moisture** (i.e., moisture level prior to a rain or wind event), porosity, surface roughness, texture, and **aggregation** (i.e., binding together of individual soil particles). Individually, these properties have varying, dynamic, and interdependent effects on erosion rates (Römkens et al. 2001).

Antecedent soil moisture is the single most important property influencing erosion during storm events because it affects the structure and hydraulic response of the soil (Cresswell et al. 1992). In general, wetter soils will saturate quicker during a rain storm and thus produce overland flow sooner, resulting in more potential for erosion. However, wet conditions can result in more ponding on the surface, which can protect the soil from raindrop impact (Hairsine et al. 1992). In general, soils with < 30 percent moisture break down and form a **seal** (i.e., condition where surface porosity is reduced by plugging by soil particles or compaction) faster than soils with > 30 percent moisture, especially with rapid wetting (Le Bissonnais et. al. 1989; Luk 1985). Soil seals form by raindrop impact and by sediment deposition from the infiltration of sediment-laden overland flow (Moss 1991). Seal development impedes infiltration and increases overland flow, and therefore, erosion potential (Poesen 1993). However, under some conditions, a seal can decrease erosion rates because it increases soil shear strength (Römkens et al. 1997). Soil aggregates, or peds (Figure 3) (Pierzynski et al. 2005), generally experience an exponential increase in shear strength from almost zero at saturation to their highest potential strength at their plastic limit (Tengbeh 1993). Frequent wetting and drying cycles decrease aggregate stability and increase erodibility (Tisdall et al. 1978; Shiel et al. 1988; Römkens and Wang 1987). The breakdown of aggregates is fastest under rapidly wetting conditions (LeBissonnais et al. 1989; Lado et al. 2004). The increased aggregate breakdown is due to **slaking**, which is the process of air escaping from soil pores as water moves in (Rudolf et al. 1997).

Soil porosity is the single most important control on infiltration rates. Soils with high surface porosity have greater infiltration rates and less runoff, thereby limiting erosion (Pierzynski et al. 2005). **Porosity** is a function of the small-sized (micropores) and intermediate-sized spaces (mesopores) among individual soil particles and the larger spaces between peds (macropores) caused primarily by biological activity (Brooks et al. 2013). Macropores connected to the surface have the ability to transmit large quantities of water quickly away from the surface, thereby maintaining high infiltration rates.

In the absence of vegetation, **surface roughness** is the major factor affecting soil seal development, runoff, and erosion (Cogo et al. 1983). Rougher surfaces generally delay sealing because the increased relative surface area of the soil creates lower raindrop impact density (Roth and Helming 1992). Rough surfaces also have depressions where ponding occurs, increasing the surface storage of rain water and decreasing runoff velocity (Hairsine et al. 1992; Onstad 1984). On small test plots, ponding decreased the amount of surface smoothing (Rudolf et al. 1997), but on larger plots leveling was greater when ponding occurred (Bertuzzi et al. 1990). The larger plot allowed runoff to reach a higher velocity, and

Figure 3. A forest soil showing peds or aggregates of individual soil particles near Parsons, West Virginia (Photo credit: Adrienne Nottingham).

therefore, greater shear stress. Surface roughness has a large effect on rill development (Römkens et al. 2001). Greater surface roughness may increase rill development by concentrating flow (Abrahams and Parsons 1990; Helming et al. 1998; Römkens et al. 2001).

Soil **texture** affects infiltration and runoff rates, soil shear strength (Poesen 1993), and aggregate stability (Lado et al. 2004). Clay content plays a major role in aggregate stability and seal formation (Lado et al. 2004). Aggregates of 1:1 type clays are stronger than aggregates formed by 2:1 clays (Troeh et al. 1999). Ben-Hur et al. (1985) found soils with intermediate clay content (10 to 30 percent) resulted in weak aggregates that broke down under simulated rainfall, providing loose, easily erodible soil that formed an infiltration seal and reduced soil porosity. The combination of loose soil and reduced porosity increased erosion potential. However, soils with < 10 percent clay content did not have enough clay to form a seal or reduce porosity when exposed to raindrop impact; therefore, they maintained high infiltration rates and low erosion potential. Clay contents above 30 percent provided sufficient aggregate stability to resist slaking and seal formation under the simulated rainfall conditions, thus, reducing detachment and overland flow, and erosion potential. Poesen (1993) found a silt loam soil resisted aggregate breakdown and maintained high infiltration rates. However, soil seals formed faster as sand content increased to 90 percent, while 100 percent sand resulted in no surface sealing and high infiltration rates. Quansah (1981) observed that sand, with the lowest cohesion of all soil types, had the highest splash-detachment rates, followed by clay, then clay loam. Splash transport was highest for clay because less energy is required to move smaller clay particles than sand particles (Quansah 1981).

Large soil aggregates require more energy to transport than small aggregates; therefore, they strongly resist erosion unless they are broken into smaller pieces (Hairsine and Rose 1992). However, large aggregates resist breakdown more than smaller aggregates (Freebairn et al. 1991). In addition to size, antecedent moisture (Truman et al. 1990), organic matter content, soil cations (i.e., positively charged ions), clay content, and clay mineralogy influence aggregate stability (Haynes and Swift 1990; Perfect and Kay 1990). Slightly acidic soils (pH range of 4.5 to 6.0) tend to form more stable aggregates than those with high amounts of sodium, magnesium, and potassium (Troeh et al. 1999). Organic matter can act as a binding agent and help to form stronger aggregates as well (Tengbeh 1993; Troeh et al. 1999; Traore et al. 2000).

Precipitation Characteristics and Erosion

As the primary means of water input to landscapes, precipitation can exert a significant influence on erosion. Precipitation is characterized by amount, duration, intensity (i.e., amount/duration) and sequence (i.e., the order and timing of rainfalls) (Meyer 1981). Rainfall intensity is usually the most important of the four factors affecting erosion (Nichols and Sexton 1932). As intensity increases so does the kinetic energy of the raindrops, increasing detachment and transport of soil (Ellison 1944; Quansah 1981). The intensity and size of raindrops are important because the force of raindrop impact can compress or collapse soil pores and detach soil particles, which can further plug soil pores and increase runoff (Moss 1991). Climate change models predict that the earth will experience more intense storm events, resulting in greater erosion rates (Intergovernmental Panel on Climate Change 2015).

Increases in rainfall duration increase the erodibility of soil (Tisdall et al. 1978). As rainfall volume increases with duration, soil becomes saturated. After saturation, surface runoff develops, which has the potential to transport sediment and increase erosion rates (Pierzynski et al. 2005). Soil shear strength decreases exponentially as the soil approaches saturation (Tengbeh 1993), resulting in increased potential for sediment entrainment in overland flow.

The sequence of rainfall events is important because it directly affects some soil properties, primarily soil moisture. As discussed previously, soil moisture affects soil shear strength. Greater periods of time between rainfall events generally result in drier soils, while frequent rain events lead to more consistently moist soils. Recently deposited soil from previous storms is more erodible due to poor aggregation (Hairsine et al. 1992), and frequent rainfall events can lead to decreasing sediment yield due to flushing (i.e., transport of stored sediment) (Croke et al. 2006). When frequent precipitation occurs, easily erodible soil is detached and transported during the first few storms, leaving less erodible soil for subsequent storms. This can result in decreasing erosion rates from rain event to rain event, assuming the storms have similar rainfall characteristics.

Topographic Influences on Erosion

Slope steepness and length are critical factors controlling overland flow and erosion (Bryan and Poesen 1989). As the slope increases, so does the probability that splashed soil will move downslope (Ellison 1944). In a laboratory experiment, Quansah (1981) found that detachment rates increased slightly, and sediment transport capacity increased greatly on steeper slopes. Steeper slopes also enhance erosion via rill development due to increased shear velocities (Chaplot and LeBissonnais 2000). On sloping land, there is usually net transport of soil downslope because displaced soil can travel further downhill than uphill due to gravity and slope angle. On a 10 percent slope, up to 75 percent of the splashed soil can move downhill (Ellison 1944). Huang et al. (1999) found that slopes < 5 percent resulted in net sediment deposition during simulated rain events in a laboratory experiment. On relatively flat surfaces, raindrop splash causes essentially no net soil loss because displaced particles are replaced by nearby soil particles that were displaced by raindrop impacts (Troeh et al. 1999).

Long slopes generally result in high amounts of soil loss (Troeh et al. 1999; Brooks et al. 2013). However, the effects of slope length are complicated by the processes of seal development, rill development, and deposition. All of these processes have varying effects on infiltration and runoff and can occur simultaneously (Bryan and Poesen 1989). Research suggests that slope length is not an important factor affecting runoff velocity on grades < 8 to 10 percent (Chaplot and LeBissonnais 2000; Kinnell 2000). At lower gradients, runoff reaches a relatively low maximum velocity in a short distance (e.g., 4 percent slope at 3 m). As slope increases, maximum potential runoff velocity increases along with the distance required to reach that velocity (Chaplot and LeBissonnais 2000). Greater runoff velocity results in greater transport capacity and erosion rates (Table 1) (Chaplot and LeBissonnais 2000).

Table 1. Erosion rates under different surface slopes and plot sizes following a 30 mm h^{-1} simulated rainfall (from Chaplot and LeBissonnais 2000).

Slope (%)	Surface Area (m^2)	Soil Loss (g $m^{-2}h^{-1}$)
4	1	60
4	10	70
8	1	90
8	10	190

Biological Influences on Erosion

Vegetation

It is well documented that soil covered with vegetation or vegetative litter is less erodible compared to bare soil (Swift 1984; Quinton et al. 1997; Loch 2000; Freebairn et al. 1986). The greatest reductions in soil losses occur as cover increases from 0 to 30 percent (Quinton et al. 1997; Loch 2000). Loch (2000) found exponential decreases in sediment yield with increasing grass cover, and once cover reached 23 percent, rill development ceased. At 50 percent cover, sediment losses were < 0.5 metric tons ha^{-1}, regardless of runoff rates.

As precipitation falls, the first defense that vegetation provides against erosion is raindrop interception. However, mature tree canopies can actually increase the kinetic energy of raindrop impact by aggregating precipitation into larger droplets and releasing them as throughfall to the ground (Stuart and Edwards 2006). Despite this effect, the litter layer associated with forest floors under mature trees protects the soil from raindrop impact (Stuart and Edwards 2006). The litter layer also provides organic material which can increase aggregate stability (Tengbeh 1993) and can store a large amount of water (Brooks et al. 2013). Shade provided by stems, leaves, and litter slows soil drying rates, which may increase aggregate stability compared to aggregates forming under rapid drying conditions (Tengbeh 1993).

Vegetation also increases infiltration (Loch 2000) and surface roughness via rooting and by providing a litter layer (Walsh and Voigt 1977; Woo et al. 1997). Vegetation and litter increase roughness on slopes in the form of debris dams and blockage of water movement by stems. These obstructions can increase the depth of overland flow and decrease its velocity (Hairsine et al. 1992; Yu et al. 2006; Woo et al. 1997). Increased flow depth can reduce detachment by padding the soil against raindrop impact (Hairsine et al. 1992). Gyssels and Poesen (2003) showed that rill formation decreased as grass shoot densities increased in highly erodible soils, and soil deposition occurred in meadows. Mature and dense grass stems were important in controlling erosion because the stiffer stems were able to resist the force of overland flow. By contrast, younger field crops are susceptible to being bent over by concentrated flows (Gyssels and Poesen 2003). Analogously, in the early stages of plant growth, roots are more important in controlling rill development because young shoots bend or break with heavy flow (Gyssels and Poesen 2003). Dense, heterogeneous cover is ideal for limiting rill erosion (Gyssels and Poesen 2003). Abrahams et al. (1995) found decreased infiltration and increased runoff in rangeland that had converted from primarily grasses to shrubs because the soil between shrubs was eroded by raindrop splash and rills; this occurred even though the soil was well protected directly beneath the shrubs.

Roots physically reinforce and bind soil in place, resisting erosion from concentrated flow (De Baets et al. 2006; Gyssels and Poesen 2003; Tengbeh 1993). Tengbeh (1993) found a minimum of 500 percent increase in soil shear strength when fibrous grass roots were present compared to bare soil. The increase in shear strength due to root presence depends on soil texture. Tengbeh (1993) found a clayey soil with roots had 1.7 times greater shear strength than a sandy soil with the same root density. The higher shear strength of the clay soil was attributed to stronger cohesion of the clay soil to the roots. Root growth and dieback result in more pore space and connectivity, which increases infiltration and reduces erosive overland flow (Gyssels and Poesen 2003; Loch 2000; Yu et al. 2006). Roots secrete organic binding agents

Figure 4. Standard soil erosion plots and simulated rainfall system in southern Indiana in 1968. These types of experiments were used to develop and refine the Universal Soil Loss Equation (USLE) (Photo credit: USDA Agricultural Research Service).

that increase soil aggregate stability (Tengbeh 1993; Traore et al. 2000). These exudates provide sustenance for many soil organisms that increase porosity and secrete binding agents themselves (Traore et al. 2000), thereby further increasing aggregate stability and reducing erodibility (Troeh et al. 1999).

Soil Organisms

Vegetation increases the value of habitat for burrowing invertebrates and rodents whose tunnels increase soil porosity and the formation of macropores (Loch and Orange 1997). These organisms mix material through the soil profile, transporting organic matter away from and coarse particles toward the soil surface (Pierzynski et al. 2005). Earthworms are among the most abundant (Pierzynski et al. 2005) and most studied soil organisms (Blanchart et al. 2004). Through burrowing and feeding activities, earthworms enhance the physical and chemical structure of most soils by creating macropores and transporting organic matter through the soil profile (Lee and Foster 1991). Earthworm activities increase the infiltration capacity of soil (Ehlers 1975; Shipitalo and Butt 1999) and reduce runoff (Kladivko et al. 1986). In compacted soils, earthworms decrease bulk density and increase infiltration (Joschko et al. 1989). However, earthworm castings on the soil surface and animal excavation can expose mineral soil to raindrop impact and potentially increase erosion (Binet and LeBayon 1999; Yair 1995).

Measurement of Surface Erosion

Erosion can be physically measured by erosion plots and erosion stakes or pins. **Erosion plots** are the most widely used method and consist of rectangular plots of specific size where the amount of eroded soil is collected down slope of the plot during and following natural or simulated rain events. The boundaries of the plots consist of walls of sheet metal, plastic, plywood, or concrete. A collection trough and container are installed on the downslope side to capture the runoff and sediment. The standard plot size is 6 feet by 72.6 feet (approximately 2 m by 22 m) that was used in the development of the Universal Soil Loss Equation (USLE) (Figure 4). The USLE was developed by the United States Department of Agriculture, Agriculture Research Service in 1965 as a means to predict erosion over a broad set of surface conditions and climates (Brooks et al. 2013). For more detail on the USLE Equation, see Schoonover and Crim (2015, this issue), "An Introduction to Soil Concepts and the Role of Soils in Watershed Management." Erosion can also be measured from microplots 1 to 2 m^2 in size, which are commonly used in research studies.

Surface erosion and deposition are measured at multiple locations over time by installing **stakes** or **pins** in the ground surface. Upon installation, the height of the stake is measured above the ground surface and then re-measured at various time intervals (week, month, year) to estimate the amount of soil loss or accumulation. The erosion stakes can be arranged in various grid patterns along a slope or field to estimate erosion and deposition at different topographic positions.

Surface Erosion in Forests and Agricultural Fields

The most important factor controlling surface erosion in forests is the annual supply of litter to the forest floor (Stuart and Edwards 2006). The litter layer absorbs the kinetic energy of raindrop impact (Kochenderfer 1970) and provides organic material to the soil, which is a food source for soil organisms (Stuart and Edwards 2006). Dense root networks in forests provide soil stabilization, while root dieback increases pore space (Loch 2000). Porosity also is increased by burrowing rodents (Pierzynski et al. 2005). Consequently, forest infiltration rates are generally very high (Patric 1978; Kochenderfer 1970). Overland flow rarely occurs in forests where an intact litter layer is present (Stuart and Edwards 2006). Thus, forests experience little rill or interrill erosion (Patric 1978).

Agricultural fields commonly experience more erosion than forests mainly due to a lack of ground cover and greater amounts of exposed mineral soil. Additionally, agricultural soils tend to be more compacted than forest soils because of farm machinery traffic. Compaction collapses macropores and results in lower infiltration rates, more runoff, and greater erosion. Further, tillage (i.e., disturbing the topsoil to prepare a seed bed and provide weed control) can reduce surface residues, soil macroporosity, and aggregrate stability, thereby increasing erosion potential. Reduced tillage or no-till can help reduce erosion rates by allowing more surface residue and macropores to develop through increased soil biological activity. Since the surface of agricultural fields is irregular and has microtopography, the area is commonly drained by concentrated overland flow and rills (Pankau et al. 2012). Thus, rill erosion usually greatly surpasses interrill erosion in agricultural fields. For example, Govers and Poesen (1988) found 75 percent of eroded soil resulted from rill erosion compared to 25 percent from interrill erosion.

Erosion Control

Erosion control can take many forms in many different activities. Mechanical, physical, and biological methods all can be used to reduce erosion and control sedimentation or locations of sediment deposition. Many of these methods are generally considered under the umbrella term of **best management practices** (**BMPs**), and they are used in agriculture, construction, forestry, mining, and other land uses in which erosion is a concern. BMPs are designed to reduce erosion at optimized cost, and they are based on physical principles that influence the energy of water and the erodibility of soil (Stuart and Edwards 2006).

Managers are well aware of the benefits of vegetation for soil stabilization, so revegetating disturbed sites is a fairly common BMP (Troeh et al. 1999; Kochenderfer 1970). The revegetation process often includes soil amelioration (ripping compacted soils, fertilization, liming, etc.) and seeding followed by mulching, but also can be as simple as casting seed (Kochenderfer 1970). Vegetative species selected for erosion control usually are prolific, fast growing plants with fibrous root systems that are able to rapidly cover bare soil and hold it in place (Troeh et al. 1999). In agricultural watersheds, cover crops, such as grasses and legumes, can be planted in the fall to provide ground cover and limit erosion during the dormant season. See "Guiding Principals for Management of Forested, Agricultural, and Urban Watersheds" (Edwards et al. 2015, this issue) for more detailed information on erosion control and best management practices.

Conclusion

As sediment is the most common water pollutant worldwide, it is important to understand the dominant factors influencing erosion rates to help minimize sediment delivery to surface water bodies and protect aquatic biota. In humid climates, precipitation intensity, soil moisture, slope steepness, slope length, vegetation, and soil organisms interact to determine a watershed's vulnerability to erosion. In forested and agricultural watersheds, BMPs are designed to limit the exposure of mineral soil to rainfall and surface runoff and thus reduce the detachment and transport of sediment. Land managers and owners can limit erosion by following two simple tenants: 1) maintain as much ground cover as possible during land management activities (farming, timber harvesting) and 2) rapidly establish ground cover following periods of active land management. Practicing these two rules will provide low-cost, effective, and long-term erosion control that will help keep working landscapes productive.

Acknowledgement

This work was supported by funds provided by the USDA Forest Service, Monongahela National Forest.

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