3

Erosion and Principles of Soil Conservation

3.1. Definitions

It is common to distinguish two main types of erosion:

– natural erosion (Figure 3.1). Also called denudation or geologic erosion, it has occurred since the continents were exposed to mechanical and chemical processes (see below) and still continues to occur. It is studied over long periods (>10,000 years) and is often expressed in mm/1,000 years (see the volume in this series *Soils as A Key Component of the Critical Zone 4: Soils and Water Quality*);

– accelerated erosion by human action. It is often expressed in tons ha^{-1} year^{-1}. It manifested itself from the – deliberate – fires of the savannah, but was clearly amplified in the Neolithic period [FRO 16] and even more so in the Anthropocene period [FOU 14].

And two main processes:

– mechanical erosion defined by a process comprising three mechanisms:

- fragmentation or detachment under the effect of very diverse agents: freeze/thaw, friction (glacial erosion), wind (wind erosion), impact of raindrops and runoff (water erosion), mass movements, effect of waves and currents (coastal erosion), tillage (soil erosion) and harvesting of roots or tuber crops;

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- transport of loose particles;

- their sedimentation or deposition (see section 3.3);

– chemical erosion, which refers to the transport of solutes resulting from the dissolution of rocks by weathering, and more generally of any solute transported by runoff or water tables.

Figure 3.1. *Example of essentially natural erosion in the sparsely populated upper catchment of Yángzǐ Jiāng, Shigu, Hailuo Mountains, Yunnan, China. Note: the cloudiness of the water (photo: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

This chapter focuses on the accelerated and mechanical erosion of continental soils and the main principles of soil conservation.

3.2. The importance of erosion

3.2.1. *On a global scale*

As already reported in the first Global Assessment of Human Induced Soil Degradation (GLASOD) [OLD 91] and confirmed by the FAO Report on the Status of the World's Soil Resources published at the event of the International Year of Soil [FAO 15], erosion is the main form of soil degradation, both globally and in each of the eight major geographical regions. This report estimates global water erosion at 20–30 Gt year^{-1} and tillage erosion at 5 Gt year^{-1}. This represents average losses of 12–15 tons ha^{-1} year^{-1} [DEN 03], or the equivalent of 1 mm per year, which is one or two orders of magnitude greater than soil thickening by pedogenesis [MON 07a, STO 14]. In other words, the soil renews itself less quickly than it erodes under the effect of man. Thus, the Anthropocene is characterized, among other things, by the fact that soil can no longer be considered as a renewable resource, because of the type of mining exploitation by man [HOF 15]. The critical zone is thus reduced more rapidly by mechanical erosion at the surface than it is formed at its base by biogeochemical processes [AND 07b]. Moreover, failure to take erosion into account can lead to a strong overestimation (17%) of the potential for atmospheric carbon sequestration by soils [CHA 15]. However, these general considerations mask large disparities associated with many components of the critical zone: type of vegetation cover, rock, land use, slope, climate, and spatial and temporal scale of measurements.

3.2.2. *Effects of erosion*

We will briefly discuss three consequences of erosion, distinguishing between on-site and off-site effects, and historical consequences.

On-site effects mainly concern soil quality. The erosion of the surface horizon (horizon A) is manifested by a selective loss of the finest elements (clay then silt) and organic matter under the effect of runoff or wind. However, it is clay and organic matter that make it possible to store fertilizing elements. The erosion of the surface horizon therefore has an immediate effect on the chemical fertility of the soil. Nutrient losses through crop erosion and export are offset globally by the use of nitrogen fertilizers. However, the use of phosphate fertilizers is far from compensating for erosion losses, particularly in Africa and Southeast Asia [QUI 10] Moreover, by depleting the soil of organic matter, erosion decreases its structural stability, enhances the formation of surface crusts (see Chapter 2) and runoff, thus inducing self-acceleration of detachment processes. Once the surface horizon has been removed by erosion, horizon B is exposed, which is often richer in clay. This raises tillage problems. A clay-rich soil rich only offers an optimal range of reduced moisture to be tilled: if it is too dry, it is too hard and requires a lot of energy; if it is too wet, it is too sticky, or fluid, and compacts easily. If erosion reaches the B/C and then C horizons, then large quantities of coarse fragments make the soil difficult to cultivate. Lastly, when the soft soil has completely disappeared, it is very difficult to consider a crop or even a plantation of trees. Furthermore, by reducing soil thickness, erosion causes a decrease in rooting volume and soil water reserves. As a result, erosion greatly reduces the main functions of soils and their land value.

This role of erosion on soil quality and function is generally well known to farmers. Thus, a survey of farmers in northern Laos [LES 12] (Figure 3.2) revealed that the first indications of soil degradation linked to cultivation was its change in color (which reflects the reduction in organic C content), then the appearance of coarse fragments on the surface (and therefore that of the B/C or C horizons), rills and gullies (which cut deep into the soil), and landslides (which often remove all the soft horizons all the way to the bedrock). Correspondingly, the density of fallow vegetation is decreasing, and its color tends to change and be more yellow (indicative of a nitrogen deficiency). The multiplication of crop cycles/fallows and the reduction of the fallow period also lead to the invasion of more and more noxious weeds, which in turn lead to an increasing amount of weeding and thus to agricultural erosion [DUP 09].

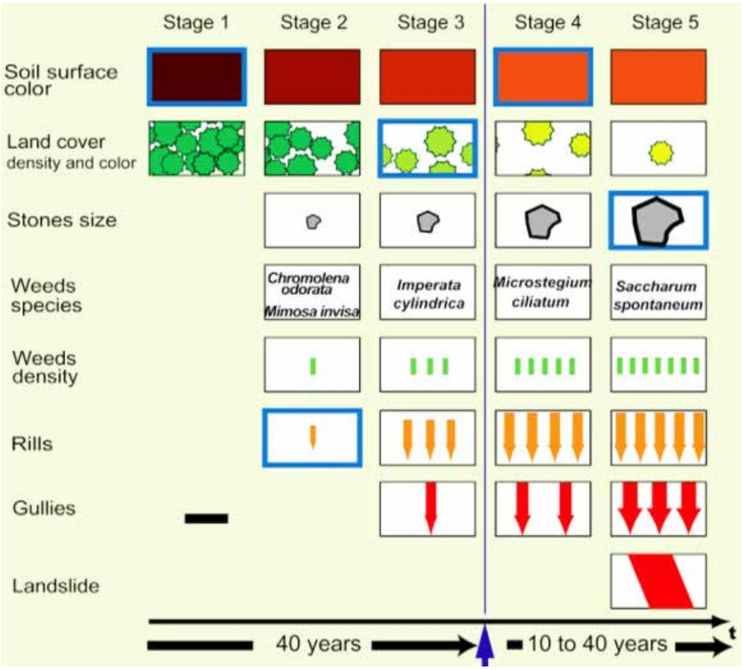

Figure 3.2. *The perceived stages of land degradation by farmers in the Houay Pano catchment, northern Laos, from the initial state 40 years ago (Stage 1) to Stage 5, forecasted between 10 and 40 years according to the plots. The main criteria used by farmers were soil color, density and color of vegetation, abundance and size of coarse fragments on the surface, increasingly noxious weed species and their density, density of rills, gullies and landslides (adapted from [LES 12]). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

Off-site impacts concern impacts downstream of detachment areas, and therefore transport and deposition: siltation and silting of reservoirs and rivers, water quality, pollution, but also transfers of fertility.

Suspended loads, also called suspended solids (SS), that are generally transported over long distances, make the water turbid (Figure 3.3). When transport velocities are no longer sufficient, especially in plains and deltas, sand and silt can settle and gradually raise the beds, causing flooding. The Yellow River (Huang He), which takes its name from its high turbidity acquired during its crossing of the great Loess Plateau, or Huangtu Plateau, has thus changed its bed many times over the last few millennia, its delta having moved 480 km [XUE 93].

Figure 3.3. *Betsiboka River estuary in Mahanjanga, northwest of Madagascar, which drains the island's largest catchment (49,000 km²) and exports the equivalent of 3,600 t km^{-2} $year^{-1}$[CHA 93] in sediments (photo: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

In addition to more frequent flooding, siltation and silting of waterways induce habitat changes for aquatic fauna and fill in spawning grounds. They require the raising of embankments and bridges and the dredging of waterways and irrigation channels. Siltation of dam reservoirs considerably reduces their lifespan. This phenomenon is particularly distinct in small dams in semiarid environments. For example, the 34,380 m^3 of Sadine reservoir in central Tunisia was completely filled up with sediments in a single rainfall [NAS 04]. For large dams, reducing the life of reservoirs for irrigation or hydroelectric production due to siltation represents a considerable cost, hence the importance of limiting erosion from their catchments [ANN 16]. Incidentally, the quality of continental waters is not only directly influenced by chemical erosion through runoff and water table runoff, but also, and above all, by runoff and particles detached by erosion (sediments). Since the sediments transported by water table erosion come from the surface horizons, they are enriched with clay and fine silt (selective erosion of fine particles), organic carbon [RUM 06] and phosphorus compared to soils in place, leading to risks of eutrophication downstream [KLE 11]. The same is true for heavy metals, pesticides [SAB 14] and pathogenic bacteria such as *Escherichia coli* [ROC 16].

However, sediment transport and deposition do not only have negative aspects, since they allow fertility transfer from slopes to lowlands (Figure 3.4), from mountains to deltas and oceans, and from deserts to humid tropical areas (for wind dust – see section 3.4.5).

Figure 3.4. *An example of fertility transfer from previously cultivated hills and highly eroded mountain to terraced valley bottoms that retain some of the sediment, organic carbon and nutrients, Jiangxi province, China (photo: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

Without the natural erosion of the Ethiopian mountains and the silt-laden floods of the Nile, would Egyptian civilization have seen the light of day? For the first 15 years, the impoundment of the Aswan dam caused a collapse of fisheries in the south-eastern part of the Mediterranean, due to the lower inflow of nutrients contained in sediments to marine phytoplankton. It is the intensive use of fertilizers, especially phosphate fertilizers on crops, that has allowed fish stocks to recover [NIX 04]. Similarly, many regions in the world (northern Europe, the great plains of the United States, the Loess Plateau of China) still derive their richness from the fertility of their soils formed on silty sediments, resulting from periglacial wind erosion, the loess.

A contrario, erosion is often blamed [DIA 05] for having contributed, along with other factors such as climate change, to the decline of civilizations (e.g. the Mayan Empire), or even to demographic collapses (e.g. Easter Island). The most frequent scenario [MON 07b] dawns with the demographic saturation of the most fertile valleys, which leads to the land-clearing of sloping soils. Such a phenomenon can still be observed in several countries in Southeast Asia, where cultivation on steeply sloping soils, particularly corn and cassava, causes considerable soil losses [VAL 08].

3.3. Processes and factors

Any erosion process involves three mechanisms: soil particle detachment, transport and deposition. We differentiate here between the largest erosion processes according to detachment mechanisms and the factors that determine them.

3.3.1. *Splash detachment*

The first detachment process is the one relating to the impact of raindrops. The largest ones (Figure 3.5) can reach a diameter of 5.5 mm and a terminal velocity slightly less than 10 m s^{-1}, which represents considerable kinetic energy, in the range of 810^{-6} J (joules) for a single large drop and 35 J m^{-2} mm^{-1} for the highest of rain intensities. The droplet size distribution is now measured automatically with the help of disdrometers. The impacts of the drops riddle the surface with microcraters, which attest the detachment of particles and their compaction. The particles detached by splash are transported by droplets (Figure 3.5) at a height of up to 40 cm and decimetric or even metric distances, the fine sands being projected the farthest. On slopes, the distances are always greater downstream than upstream, so that even in the absence of runoff, the splash detachment causes a loss in soil upstream and an enrichment of soil downstream. As the particles fall to the ground, they reorganize themselves to form structural crusts, either by micro-illuviation or by compaction (see previous chapter). These crusts reduce surface porosity, promote runoff, and export detached particles by splash (see section 3.3.2).

The soil losses corresponding to these processes – detachment and transport by splash and runoff – is most often measured on small scales, on plots of 1 m² [POD 08] or even smaller, with other processes occurring on longer slopes (see following sections). In order to control soil moisture conditions, rain intensity and duration, field (Figure 3.5) and laboratory rain simulators are often used. One of the key objectives of these simulators is to reproduce conditions as close as possible to natural rainfall, particularly in terms of drop size, ground impact velocity and kinetic energy.

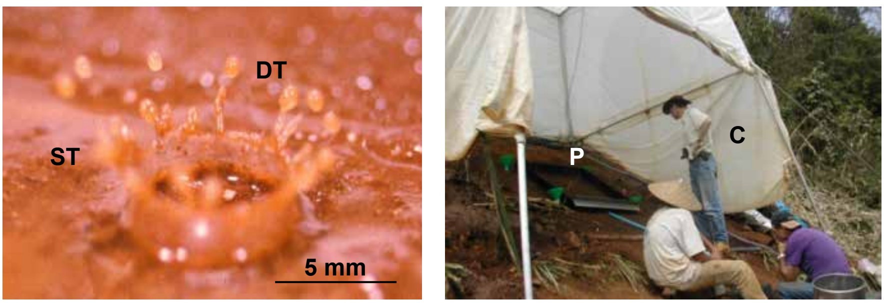

Figure 3.5. *On the left: impact of a drop of water on the soil promoting detachment (DT) and transport of soil particles in splash droplets, rearrangement of these particles and formation of a structural crust (ST), clay-silt soil, Agadez, Niger. On the right: ORSTOM-IRD rain simulator watering an area of about 8 m², in which is located a plot of 1 m² (P) where runoff and soil loss measurements are made, the whole is protected by a canvas (C) in order to avoid fluctuations in rain intensity linked to the wind, catchment of Houay Pano, Laos (photos: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

The main factors that influence the intensity of splash are:

– soil texture: fine sands are the most sensitive;

– the kinetic energy received. This depends on the intensity of the rains, the protection of the soil from the direct impact of drops (near-surface vegetation cover, organic residues, litter, mulch, etc.), but also on the slope angle. Thus, for slopes of short length, there will be less soil losses for steep slopes (low kinetic energy due to a cosine angle with reduced impact) than for gentle slopes (see Chapter 2).

In other words, there will be maximum splash for bare soils on nil or very gentle slopes that are rich in fine sands and are subjected to intense rainfall, as is typically the case in many semiarid areas and particularly in the Sahel. The soil protected from the impact of raindrops is not affected by this erosion by splash. The result is pedestal features (Figure 3.6).

Figure 3.6. *Effect of erosion by splash on the soil surface with formation of pedestal features (P); roots and coarse fragments protect the soil from the impact of drops, teak plantation where litter is consumed by termites, and understorey, considered competitive with tree growth, is destroyed by farmers, Houay Pano catchment (photo: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

3.3.2. *Sheet erosion (also called inter-rill erosion)*

As indicated in Chapter 2, runoff occurs most often when rainfall intensity exceeds the infiltrability of the soil (Hortonian runoff), which is all the more reduced when surface crusts have formed on the soil surface under the impact of the drops (see the previous section). This difference in rain intensity and infiltration results in the formation of puddles in small surface depressions. If the rain lasts long enough, these small puddles overflow and feed a relatively uniform runoff, hence the term “sheet” runoff, even on gentle slopes (Figure 3.7). This type of runoff is often manifested by the formation of microsteps, particularly on steep slopes (Figure 3.7, [RIB 11]).

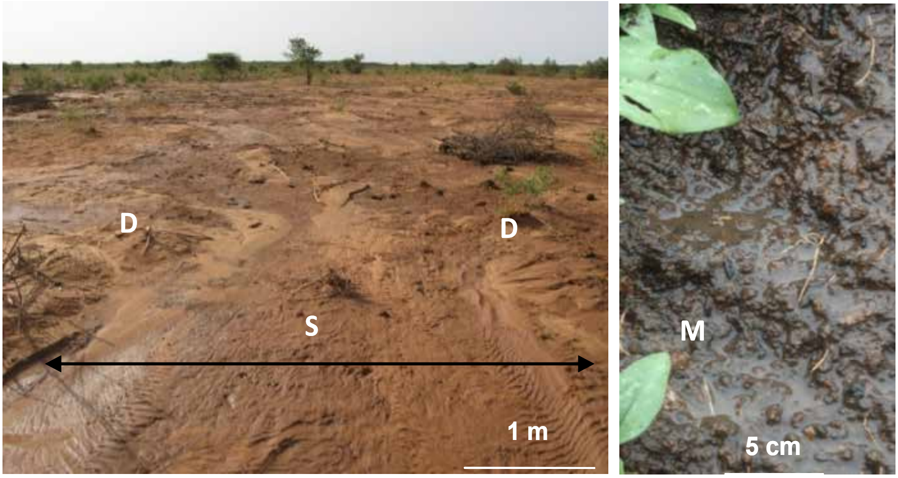

Figure 3.7. *On the left: Sediments (S) deposited during sheet flow on gentle sloping, crusted sandy soil between two microdunes (D), Banizoumbou catchment, Niger. On the right: runoff and sheet erosion, on steep slopes e, with formation of microsteps (M), Houay Pano catchment, Laos (photos: C. Valentin, O. Ribolzi). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

Contrary to what researchers estimated before the 1950s, particle detachment remains low during sheet flow (also called inter-rill flow). It transports and deposits particles, which is most often detached beforehand by splash. However, as soon as runoff velocity reaches a threshold (see section 3.3.3), it incises the soil and becomes concentrated. The first marks of this concentration appear in the form of microrills that are often less than 1 cm deep.

All soil loss due to splash, inter-rill flow and early concentrated runoff are measured on plots that are generally between 10 and 20 m long, most often under natural rainfall, but also under simulated field or laboratory rainfall (Figure 3.8).

Figure 3.8. *Swanson-type rotating rain simulator, watering 200 m² in which two runoff and erosion plots 10 m long and 5 m wide are installed, making it possible to compare two treatments, here: bare soil tilled in the direction of the slope (standard treatment, S) and a field prepared for rain-fed rice after slashing and burning (C). Two linear rain gauges (R), in yellow on the photo, make it possible to ensure the homogeneity of the rain on the two plots [COL 84], Taï forest, Ivory Coast (photo: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

The numerous data collected on plots of this type, set up from the 1930s onwards in the United States in order to measure water erosion under very varied conditions, allowed statistical treatment of the main factors (see section on models, 3.5.1). Analysis of this database (over 10,000 plot-years) [WIS 78] compared the relative importance of independent factors and statistically predicted water erosion at this scale and within the range of variation of factors used in this analysis. Thus, annual water erosion (A: erodability expressed in tons ha^{-1} year^{-1}) can be proposed as the product of five independent factors (or the sum, if this equation is in logarithmic form) in the "universal soil loss equation" (USLE) [WIS 78]:

$$A = R \times K \times SL \times C \times P$$

R, the rainfall erosivity index, (MJ mm ha^{-1} h^{-1} year^{-1}) is equal to EI_{30} accumulated over 1 year with E: kinetic rain energy during the 30 most intense minutes and I_{30}, rain intensity during the same period. Since this index can be acquired over long periods on many meteorological stations, it is possible to draw up erosion maps, also called climatic aggressiveness. Thus, for Europe, this map [NAP 15][1] shows that annual rainfall erosivity is highest (R > 1,300 MJ mm ha^{-1} h^{-1} $year^{-1}$) in the western façade of Italy (high intensities), Slovenia and Scotland (amount of rainfall), and lowest in the eastern façade of Scotland, England, Sweden and Finland (low intensities).

K, the soil erodibility index (Mg ha h ha^{-1} MJ^{-1} mm^{-1}) is calculated from the soil losses (A) measured on bare plots (C = 1, Figure 3.8), tilled in the direction of the slope (P = 1) whose value of the topographic factor SL can be calculated (see the next paragraph). As with rain erosivity, many erodibility maps have been prepared. Soils that are most susceptible to water erosion measured on a plot scale are rich in silt, low in organic carbon, subject to surface crusting and low permeability [WAN 13]. Thus, in Europe [PAN 14] K varies between 0.004 and 0.076 Mg ha h ha^{-1} MJ^{-1} mm^{-1}, with an average of 0.032 with the highest values for silty soils developed on the loess, whose organic carbon contents have strongly decreased since the decline of agriculture-livestock associations (esdac. jrc.ec.europa.eu/content/ soil-erodibility-k-factor-high-resolution-dataset-europe).

SL, the topographic factor, is the product of a slope inclination factor (S) and a plot length factor. By convention, it is equal to 1 when S = 9% and L = 22.1 m, with:

$$S = 65.4 \sin^2 \theta + 4.56 \sin \theta + 0.0654$$

$$L = (\lambda / 22.12)^m$$

θ, the slope gradient, is expressed in % and not in degrees. λ (in m) is the horizontal projection of slope length; m is a coefficient that varies from 0.2 for slopes <1% to 0.5 for slopes >5%.

C, the cover management factor, is equal to 1 (without units) when the soil is bare and tends towards 0 when the soil is fully covered near the surface. It thus expresses the ratio of erosion reduction provided by the cover to that measured on the same bare soil. It therefore depends on the

1 Available at esdac.jrc.ec.europa.eu/public_path/presentations_attachments/R-factor-developments _Final.pdf.

percentage of cover that intercepts raindrops and dissipates some of its kinetic energy, but also on the percentage of cover directly on the ground surface (creeping vegetation, litter, crop residues, coarse fragments). In a way, taking the reduction of rain kinetic energy into account, the C factor is antagonistic to the R factor. The value of C, and therefore the management of the cover, largely determines the soil losses. For example, in Europe, cropping systems based on corn s grain rotations (C = 0.47) favor water erosion twice as much as wheat and winter barley, (C = 0.24 and 0.27 [GAB 03]). Among perennial plants, forests in Finland and Sweden offer almost total soil protection ($C = 9\times10^{-4}$). Grasslands (C = 0.09) limit erosion much more than orchards (C = 0.22), olive groves (C = 0.23) and vineyards (C = 0.35) [PAN 15b]. This C factor highlights the importance of crop residues in reducing erosion. As shown in the example for sugar cane [PAU 16] (Figure 3.9), about 40–50% ground cover (47% in this example) is sufficient to divide the erosion measured on bare soil by ten.

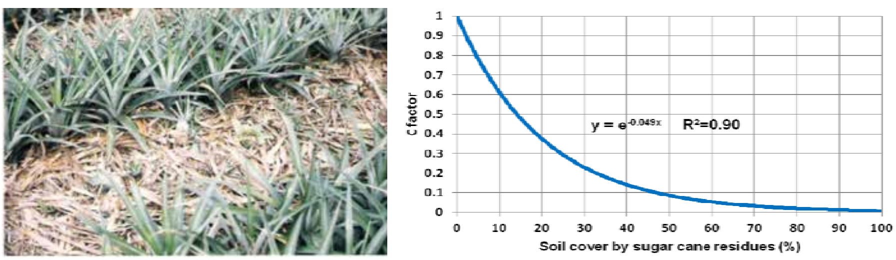

Figure 3.9. *On the left: pineapple residues covering the interrow in order to protect the soil from erosion, Adiopodoumé, Ivory Coast. On the right: coefficient of reduction of land losses compared to bare soil (C factor) based on the percentage of sugarcane residue cover in Brazil (adapted from [PAU 16], photo: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

P is a factor that expresses the reduction in water erosion associated with soil conservation practices that limit runoff velocity and therefore tends to oppose the SL factor. It is equal to 1 (without unit) in the absence of anti-erosive practice. On a plot scale, alley cropping (P = 0.025–0.05 [PAN 95]) and terraces (P = 0.05–0.18) are more effective than grass strips (P = 0.25–0.65), strip cropping (P = 0.30–0.68), or contour farming (P = 0.60–0.90) [ARA 08, GUM 11].

3.3.3. *Linear erosion*

3.3.3.1. *From the surface: rill and gully erosion*

While most studies have focused on the plot, it is rare for the runoff to remain uniform beyond that. It tends to concentrate in the depressions of the slope. If the runoff velocity reaches a certain threshold, it detaches particles by incising the soil. This velocity is frequently assessed in hydrology according to Manning's empirical formula used for free surface flows (e.g. [CHA 05a]):

$$V = (1/n)\, S^{1/2}\, R^{2/3},$$

where V is the runoff velocity (m s^{-1}), n is the Manning roughness coefficient (e.g. 0.075 for a very grassy channel as opposed to 0.010 for smooth cement), S is the slope gradient (m m^{-1}) and R is the hydraulic radius, in other words, the cross-sectional area of the flow (m^2) divided by the wet perimeter (m).

As this velocity depends on the volume of runoff, the occurrence of these incisions is directly linked to the more or less permeable surface area and conditions of the catchment, and therefore largely to land use [CHA 05b, GRE 12, POE 03, VAL 05]. Therefore, they do not only form on steep slopes (Figure 3.10), but also on all soils that tend to crust: silty soils (Figure 2.2) and sandy soils that are poor in organic C (Figures 2.4 and 2.7).

These incisions correspond to rills and gullies. There is no difference in process between rills and gullies, the distinction between the two being of an agronomic nature: a rill can be erased by tillage, but the depth and effectiveness of this depends of course on the means used, and therefore on local economic conditions.

For farmers, the development of gullies results in a loss of crop yield and available land. Moreover, gullies can also lead to changes in field distribution: from a mosaic allowing an alternation of cover favoring sediment trapping, to longer fields in the direction of the slope, which only accelerates gully erosion in a positive feedback loop [VAL 05]. In addition, gullies promote the connectivity of slopes with the waterways, which leads to:

– higher flood peaks reached more rapidly, since the runoff from the slopes is quickly concentrated and evacuated towards the outlet;

– higher losses in soil due to the rapid activity by the gullies of particles detached by splash and by incision, without the possibility of sediment trapping by the vegetation mosaic on the slopes and the riparian vegetation. In terms of quantity, linear erosion is often the main source of sediment measured at the outlet of catchments, or in lakes or reservoirs downstream [POE 03].

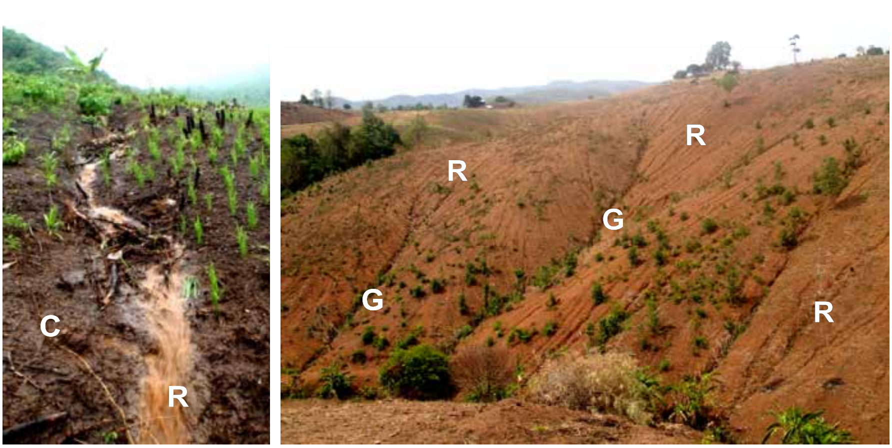

Figure 3.10. *On the left: rill erosion (R) in a rain-fed rice field at the beginning of the rainy season, after the formation of surface crusts (C), Houay Pano catchment, northern Laos. On the right: rills (R) and gullies (G) on a hillside with a steep slope, cultivated as a monocrop of corn at the beginning of the rainy season, catchment of Huay Ma Nai, north of Thailand (photos: O. Ribolzi, C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

3.3.3.2. *Within the soil: suffusion and pipe erosion*

Water movements in the soil promote sorting between fine and coarse particles. Fine particles can thus migrate vertically (leaching) and/or laterally (impoverishment). Due to soil heterogeneities, subsurface flows can concentrate in the form of natural drains which, as on the surface, depending on the flows velocity, tend to detach particles and export them. This is the suffusion (or pipe erosion) process. In earthen dikes and dams, these sinkholes may cause structures to break [FRY 12]. In soils, these tunnels often promote surface subsidence, concentration of surface runoff and its gully concentration. The roof of these tunnels can also crumble, causing aligned collapses (Figure 3.11). Therefore, soils subject to suffusion are often the places for gullies (Figure 3.11, [GRE 12, VAL 05]).

3.3.4. *Mass movements*

Soil can be eroded by the surface (sheet erosion = inter-rill erosion) or by incision (linear erosion = rill and gully erosion), but also in whole or in part of the entire mass, especially when it is wet or saturated. Geomorphologists distinguish many types of mass movements, depending in particular on their velocity [BLA 00]. Only two processes are mentioned here that can significantly increase soil losses at the outlet of a catchment: landslides and stream bank erosion.

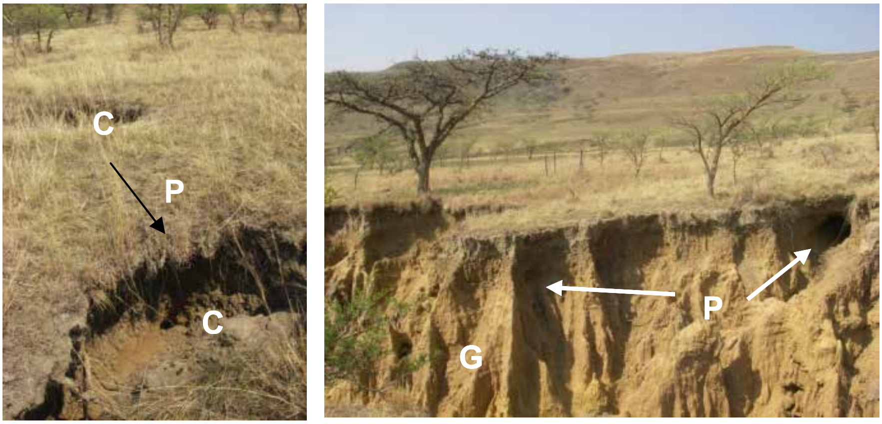

Figure 3.11. *On the left: erosion by suffosion (= pipe erosion) which is manifested here by discontinuous collapses (C) over a natural drain (P). On the right: these pipes (P) favor the formation of mega-gullies (G), also linked to a strong heterogeneity of sedimentary parent materials [GRE 12]. Potshini catchment, Kwazulu Natal, South Africa (photos: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

During a landslide, all or part of the soil and what covers it, and thus much of the critical zone, suddenly collapses along the slope (Figure 3.12). The consequences can be catastrophic, especially when cities have been built on steep slopes and these landslides result in very destructive debris flows downstream (containing one third liquid, two-thirds debris flows). The landslide trigger corresponds to a threshold combining several factors: an increase in mass (due to heavy rain, for example), on a steep slope with a water-saturated sliding surface, often between two horizons (B/C or C/R), or even between two rocks. They can thus occur on steep slopes, as well as under forest or tree planting [KIM 17] – if root fixation is insufficient to anchor vegetation firmly within the bedrock. They can also be triggered by more or less prominent seismic activities [COX 10], and channel surface runoff, thus giving rise to gullies, or even mega-gullies, such as the lavakas of Madagascar. As with earthquakes, the locations and dates of future landslides are barely predictable. However, many geophysical, geodetic, spatial remote sensing and modeling approaches make it possible to draw up risk maps [ALT 12], which should be taken more into account, particularly for building permits.

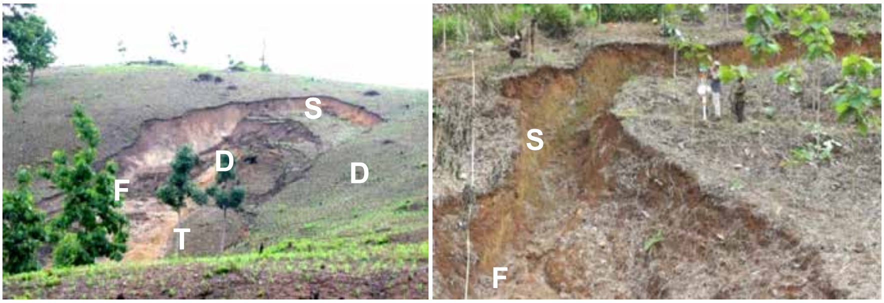

Figure 3.12. *Landslides, failure surface (F) between soil and parent materials, head scarp (S), secondary scarp (D) and toe (T). On the left: corn, Huay Ma Nai catchment, northern Thailand. On the right: young teak trees, Houay Pano catchment, northern Laos (photos: J.-L. Janeau, H. Robain). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

Streambank erosion is also an important source of sediment. It results from erosion of the foot of banks by turbulent stream flows, or from local saturation of the banks that collapse after a flood, or from a seepage zone linked to soil water exfiltration (perched water table or pipe) [FOX 07]. The trampling of livestock that come to drink from the river also contributes to this form of erosion (and to the risk of fecal pollution of the water [ROC 16]), hence the need to protect the banks and consolidate them by avoiding the clearance of riparian vegetation. In the most problematic cases, especially in the city, it is often necessary to stabilize the banks (rockfill, gabions, concrete, geotextile but also vegetation), while letting the springs run off.

3.3.5. *Tillage erosion*

On slopes, tillage and, to a lesser extent, livestock trampling detach and mobilize clods and aggregates that, under the effect of gravity, tend to move downstream rather than upstream. These aggregates are stopped by obstacles: plants and edges downstream of the field. It is therefore an erosion process, given that all three mechanisms are present: detachment, transport and deposition. In order to distinguish it from water erosion, this form of erosion is sometimes called dry erosion, but more often, it is called tillage erosion. This erosion, which increases exponentially with the inclination of the slope, can reach 7 Mg ha^{-1} year^{-1} for a slope of 60%, even with manual labor (Figure 3.13) [DUP 09], which under the same conditions is of the same order of magnitude than the losses in soil by water erosion. In addition to the slope, this form of erosion also depends on the frequency and depth of tillage [LOG 13]. In the long term, its effects smoothen landforms by leveling convex areas and filling in hollows, which is the opposite of water erosion that accentuates them due to incisions.

Figure 3.13. *On the left: tillage erosion during manual weeding on steep slopes, Houay Pano catchment, northern Laos [DUP 09]. On the right: clearer soil surface in convex erosion zones (E) than downstream – deposition zone (D), reflecting the effect of tillage erosion (E) on soil tilled for more than two millennia, Mateur, northern Tunisia (photos: B. Dupin, C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

3.3.6. *Wind erosion*

Wind erosion affects the climate (via the extinction of solar and telluric radiations and the modification of cloud properties by dust), geochemical cycles, as well as air quality and human health (via respiratory tract irritation, etc.). Like water erosion, it provides fertility transfers, often over very long distances from generally desert source areas to oceans and soils.

Wind erosion processes [MAR 14, SHA 08] involve winds that are erosive enough to move particles on the soil surface and erodible soil. This term covers two different notions:

– wind energy can be transmitted to the soil surface, so that this energy is not totally absorbed by non-erodible obstacles, such as rocks or vegetation;

– there are free particles available on the soil surface to be eroded.

This erodibility of the soil leads to the definition of an erosion threshold velocity, which is the minimum wind speed required to move the most mobile of soil particles. Ironically, it is not the smallest particles that are the first to move. Indeed, they are maintained on the ground by electrostatic forces of cohesion that are all the stronger as these particles are small. Similarly, larger particles are difficult to move because of their weight. Schematically, only grains of intermediate-sized fine sands, between about 50 and 200 µm in diameter, are directly put into motion on the surface of the soil by the wind [SHA 08]. The emission of finer particles as well as the setting in motion of larger grains require more energy than that which is directly transmitted to the surface by the wind (Figure 3.14). This is provided by the kinetic energy of fine sand grains when they fall back to the soil surface. These grains, which are too heavy to be transported in suspension in the atmosphere, move on the soil surface in successive bounds along ballistic trajectories. This is called saltation (from the Latin *saltare*, to jump). The kinetic energy provided by saltation first contributes to self-sustaining saltation. But, like the kinetic energy of raindrops, it also causes the break-up of aggregates and releases the finest soil particles (diameter <20 µm), dust or desert dust, which are then available to be transported in suspension in the atmosphere. This process of releasing the dust is called sandblasting [GIL 77]. Lastly, the energy supplied by the grains in saltation also causes the coarser particles (coarse sand and coarse fragments) to displace themselves by rolling over the surface what is called creeping. This is how gravel can cover mini-dunes by simple shifting to the soil surface.

Different measuring devices allow quantifying these processes [ZOB 03]. Creeping is difficult to estimate because it involves burying part of the devices, and maintaining the capture of particles precisely on the soil surface when the latter is very often unstable. In addition, there is always a risk of confusion with particles provided by runoff. Saltating sands can be trapped and weighed by simple passive devices, of which the most popular are the Big Spring Number Eight (BSNE) [FRY 86] and Modified Wilson and Cook (MWAC) samplers [WIL 80]. Vertical flux of dust deposition can also be measured with very simple dust traps, consisting essentially of containers whose opening is directed upwards and whose collection surface is known.

However, standard dust traps do not yet exist. Indeed, the efficiency of these dust traps seems to vary considerably, depending on their design and the wind speeds [GOS 08], so that the absolute estimate of dry deposition remains questioned. Dust emission flux measurements, on the other hand, require sophisticated devices that only a few laboratories in the world have mastered. These devices are based on the gradient method [GIL 72] and use masts to measure dynamic parameters using wind speed and temperature profiles associated with dust collection and/or dust concentration measurement at two levels (Figure 3.15).

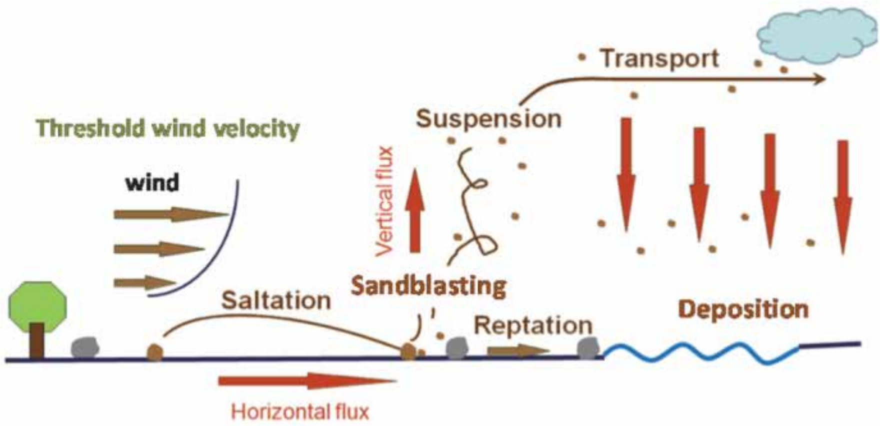

Figure 3.14. *Wind erosion process: the saltation of fine sands is only triggered above a certain threshold wind velocity. By falling back to the ground, these sands cause (1) the emission of finer particles (sandblasting), which are then transported by suspension over long distances before deposit into the oceans or over continents, and (2) creeping of coarser particles on the soil surface. For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

A great diversity of sensors placed on the ground or embedded (planes, satellites) make it possible to locate desert dust. Depending on their acquisition frequency and/or the surface area that these instruments document, they provide valuable information on dust sources and dust paths [MUH 14]. Aerosol lidars [MON 12] have the advantage of also providing the location of dust in the atmospheric layers, which is an extremely strong constraint for transport models. Although most of these instruments provide spectacular information on the spatial distribution of aerosols, they remain unreliable at present from a quantitative point of view. It is therefore particularly important to have direct and quantitative measurements, if possible over the long term, of dust concentrations and fluxes in the regions affected by wind erosion. As such, the INDAAF (International Network to study Deposition and Atmospheric composition in AFrica) observation system is exceptional: it was initially composed of three stations (Niger, Mali, Senegal), set up since 2006 in the Sahelian zone, associated with the AERONET[2] photometer network that provides, among other things, the integrated aerosol content of the atmospheric column. In addition to being able to measure meteorological parameters, the stations can also measure the mass concentration of dust at 5-min time-step and the total deposition flux at weekly time-steps[3] [MAR 10].

Figure 3.15. *Device for measuring vertical fluxes of dust using the gradient method, during a field campaign in southern Tunisia in March–April 2017 (ANR WIND-O-V[4] project). Note that the mast is equipped with cup anemometer profiles, 3D sonic anemometers and thermocouples to measure dynamic parameters, in addition to scaffolding used to collect dust particles according to their size at two levels (left photo) and to continuously measure their concentration by size class and their mass concentration, also at two levels (right photo) (photos: IRD, J.L. Rajot). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

In order to study wind erosion processes in detail, we must lastly mention wind tunnels, which are the equivalent of rain simulators for wind erosion. They can quantify the effect of certain factors under controlled (laboratory) or semicontrolled (field) conditions.

2 Available at https://aeronet.gsfc.nasa.gov/.
3 Available at www.lisa.u-pec.fr/SDT/.
4 Available at www6.inra.fr/anr-windov/.

3.4. Erosion: a question of scale

3.4.1. *Space scales*

One of the greatest difficulties in studying water and wind erosion lies in the diversity of the processes involved, each of them being scale-dependent processes. For this reason, it is imperative to mention the scale from which the measurements are taken:

– microplots (area less than or equal to 1 m^2);

– "classic" erosion plots (generally longer than 10 m), microcatchments (about 1 ha);

– small (in the order of km^2) and large basins (several tens of thousands of km^2).

As shown by a meta-analysis of 3,236 data [GAR 15], the two most frequent scales of measurement are those of 60 m^2, representing erosion plots (10–20 m long) where all sediments are collected, and those of basins of about 1,000 km^2 (where only suspended matter is generally taken into account). The differences in processes (see following sections) and loose materials (bedload, suspended matter – often referred to as "suspended load") mean that if the soil losses were expressed in a single unit (mg km^{-2}, or 10 kg ha^{-1}), they would increase slightly on average from the 1 m^2 plot (500 mg km^{-2}) to the erosion plot (600 mg km^{-2}) and then decrease regularly to 300 mg km^{-2} on a hectare scale, 200 mg km^{-2} for 1 km^2, 110 Mg km^{-2} for 1,000 km^2, 55 mg km^{-2} for 10,000 km^2 and 20 mg km^{-2} for 100,000 km^2 [GAR 15]. These data are of course only averages and do not reflect the very wide dispersion of data. However, they do illustrate that it is incorrect to extrapolate data acquired at one scale to another, as too many studies still tend to do. These are based on:

– water erosion models that do not account for linear erosion and mass movements;

– parameters from satellite imagery that tend to confuse land cover with land use.

However, depending on farming or forestry practices, the same class of cover may correspond to very different sediment production. In this respect, monospecific tree plantations that can generate significant erosion [RIB 17] should not be confused with multispecies and multistrata forests in remote sensing maps.

3.4.2. *Time scales*

3.4.2.1. *Duration of measurements*

Water and wind erosion processes are threshold dependent, and are therefore nonlinear, largely due to the importance of extreme climatic events (for example [BER 17]). Thus, the probability of measuring the effects of these events increases over time. The same meta-analysis [GAR 15], this time based on 3,053 data, clearly illustrates the importance of the duration of measurements: losses by water erosion increase on average quite regularly from 120 mg km^{-2} after 1 year of measurements to 600 mg km^{-2} for an annual average measured over 25 years, in other words, five times more. The standard error of this average steadily decreases over 20 years. In other words, the average soil losses calculated for shorter periods present great uncertainties. However, monitoring erosion over more than 20 years remains exceptional.

3.4.2.2. *Cumulative erosion – isotopic markers*

Erosion measurements require permanent equipment and field personnel, which is very costly. Consequently, these direct measurements are increasingly being replaced by indirect methods that only require soil and sediment samples to be collected. This aims at assessing erosion and sedimentation accumulated over several years at different points in the catchments. These methods are based on the quantification of radionuclides in soils and sediments. The two most commonly used markers are cesium-137 and lead-210 in excess. ^{137}Cs results from thermonuclear tests, which started in 1952 and was stopped in 1964, and more recently from accidents at the Chernobyl (1986) and Fukushima (2011) nuclear power plants. Emitted into the stratosphere, ^{137}Cs settles on the ground with precipitation and firmly attaches itself to clays. The main difficulty is then to find a reference soil profile in the study area that has not undergone erosion or sediment input to quantify local ^{137}Cs levels. With a half-life of 30.17 years, this radioisotope remains widely used as its levels remain detectable. However, its use remains questionable for sandy soils that, as in the Sahel, are affected by both the uplift and the deposit of dust. However, it is increasingly coupled with measurements of ^{210}Pb, a natural isotope (half-life 22.2 years) [HUO 13]. Beryllium 7 (^{7}Be) is used for shorter term studies, since its half-life is only 53.22 days [EVR 16]. For the assessment of erosion rates over long periods of time (>10,000 years), the nuclides of the uranium chain ^{238}U-^{234}U-^{230}Th-^{226}Ra, often associated with ^{10}Be [ACK 16], are used, and even more rarely, lithium isotopes [LED 15]. Although these measurements only require occasional field work, they do require expensive laboratory equipment and considerable expertise.

3.4.3. Space scales

3.4.3.1. *Origin of sediments: signatures (fingerprinting) of various natures*

Due in particular to the growing importance of surface water pollution by sediments, many studies are focusing on their origin. The aim is to determine erosion zones in order to better combat it. Do the sediments mainly come from sheet erosion, linear erosion, mass movements, from their remobilization in rivers, rural, industrial or urban areas? To this effect, many different approaches have been used to determine the "signatures" (or fingerprinting) of these sediments of different natures. The emphasis is generally placed more on suspended matter than on bottom sediments (also called bedloads): color, clay mineralogy, major elements and traces, rare earths, magnetic, geochemical, isotopic (^{137}Cs, ^{210}Pb, ^{7}Be, $\delta^{13}C$, $\delta^{15}N$), enzymatic and biological (e.g. pollens) properties, diffuse reflectance infrared Fourier transform spectroscopy, etc. A number of rules must be respected [HAD 13]. These markers must be conservative, must not be changed over time, or in a predictable manner, and must be capable of being used in numerical mixing models [WAL 13]. In order to improve discrimination between a large number of sources, several markers must be used simultaneously.

3.4.3.2. Transfer distances and residence times

Once detached by water or wind, sediments can be transported close or far depending on their size: the coarser particles settle quickly, often in the plot itself, while the finer particles (clays) and/or the lighter ones (litter fragments, charcoal, etc.) can be transported in suspension and by flotation over very long distances [RUM 16]. However, it remains difficult to predict the residence time of sediments within catchments. Here again, isotopic markers (^{137}Cs, ^{210}Pb, ^{7}Be) are an important tool to distinguish sediments resulting from remobilization from those linked to recent erosion [HUO 17]. Thus, the use of models based on isotopic measurements makes it possible to assess residence times, which can vary according to the size of the sediments, and of course to the size of the basin considered, ranging from a dozen of days to tens of thousands of years [VOE 13].

3.4.4. *Particulate and soluble transport*

In addition, much of the work on accelerated erosion focuses on particulate transport and not soluble transport. However, these can represent a significant share of transfers. For example, the soluble reactive phase of phosphorus represents 38% of total phosphorus exports (19.4 kg km^{-2}) measured at the outlet of a small agricultural catchment in Brittany, the Kervidy-Naizin (5 km^2) [DUP 15].

Conversely, much of the work on geological erosion from large rivers focuses on soluble flows, which are easier to measure, neglecting particulate flows. A meta-analysis of 175 tropical rivers, including 95 in Asia and Southeast Asia [TIN 12], estimated exports to estuaries as particulate organic carbon (POC) and particulate inorganic carbon (PIC) at 34% of total exported carbon. This assessment is consistent with the range of dissolved organic carbon (DOC): 73 ± 21% of total exported organic carbon (TOC), obtained from data from 550 basins around the globe [ALV 12].

3.4.5. *Aeolian dust*

According to global models, the quantities of dust emitted by wind erosion of soils largely exceed 1,000 Tg $year^{-1}$ and their average residence time in suspension in the atmosphere is less than 1 week [TEG 14]. These dusts are the equivalent of fine sediments produced by water erosion and transported in suspension in rivers to the ocean. They also travel thousands of kilometers. Depending on the magnitude of their deposition flux, all the higher if the sources are close [MAR 17], they can constitute parent material such as loess set up during the glacial period, which support some of the most fertile soils on the planet [PYE 95], or just more or less heavily influence the properties of soils or ecosystems [SIM 95]. One of the most spectacular current examples is the influence of the dust plume emitted from the Sahara/Sahel, which contributes to the fertilization of Sahelian soils (Figure 3.16), the Atlantic Ocean and the Amazonian forest, notably by a phosphorus inflow (7–39 g ha^{-1} a^{-1}) of the same order of magnitude as the quantity exported from the basin into rivers [YU 15].

The main dust source areas are therefore desert areas for which there is not, strictly speaking, soil degradation. The relative importance of anthropogenic emissions, mainly from cultivated or grazed soils in arid and semiarid zones, is difficult to estimate and mainly relies on modeling or remote sensing [GIN 12]. However, it is in these areas that the main challenges lie, in particular loss of fertility, in connection with cultivation practices [ABD 11] and the extension of cultivated areas. One of the particularly poorly known points, in the absence of measurements, is the quantity of organic matter emitted, clearly enriched in wind sediments due to its low density, which could constitute a major source of uncertainty in the carbon cycle [WEB 12].

To judge the often-positive effect of dust deposits on soils far from sources, it is important to identify the source zones and to know the composition of the dust emitted [MUH 14]. This is all the more complex because the main sources are difficult to sample, as they are located in desert areas that are difficult to access.

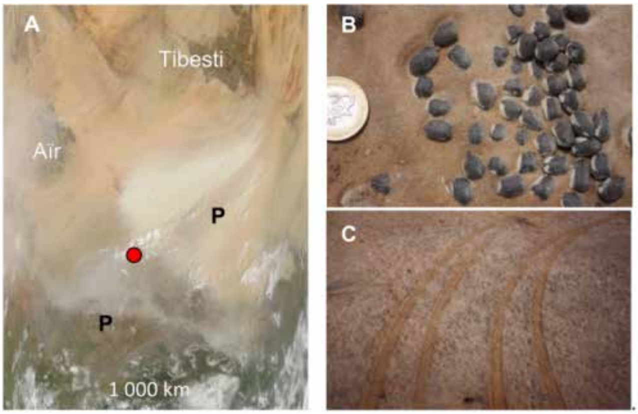

Figure 3.16. *The Bodélé depression, north of Lake Chad, is one of the main sources of dust in the world [TOD 07]. (A) Terra Modis image of a dust plume from the Bodélé depression (18/03/2010) – P: Dust plume, red dot location of photos (B and C). (B) Detail of a white dust deposit on goat droppings in the Gouré region, located in south-east Niger, more than 800 km south-west of the source zone (22/03/2010). (C) Same region, homogeneous deposit of whitish dust on the soil in an area protected by vegetation. By disrupting the surface, the car tracks make it possible to discover the normal color of the surface horizon of the sandy soil (23/03/2010) (photo: J. L. Rajot). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

3.5. Modeling

The main difficulty of modeling arises from the multiplicity of scales and processes that must be clearly defined each time. In addition, there are a variety of approaches: statistical, physically based, and hybrid.

3.5.1. *Statistical approaches*

For water erosion, the most widely used plot scale model is the USLE [WIS 78], which has been presented in section 3.3.2 on sheet erosion. Despite the warnings by Wischmeier [WIS 76], its principal author and many other researchers following him, this equation is often used on wider scales than those of the original statistical sample (see section 3.4.1). This equation has since been improved by taking the evolution over time of soil erodibility into account and proposing a new formulation of the topographic factor. This is the revised universal soil loss equation (RUSLE). In its second version, the time scale is daily. Its easily accessible parameters thus allow an assessment of water erosion[5].

Wind erosion modeling has followed the same evolution, from an equation which is rather similar to the USLE [WOO 65]. These approaches allow wind erosion risk maps to be drawn up (for example for Europe [BOR 16]). The original statistical equation [WOO 65] was subsequently revised in order for it to be applied to the event scale [FRY 01].

3.5.2. *Physically based models*

In order to better take the processes of the scale of the hillside or the catchment into account, many physically based models have been proposed: EUROSEM in Europe [MOR 98], GUEST in Australia and South-East Asia [YU 99], KINEROS[6] [SMI 95] and WEPP in the United States[7] [FLA 07]. However, their use is often hampered by a large number of parameters that are difficult to acquire, and therefore often poorly assessed, or even used as adjustment variables to obtain a correct calibration of the model. The comparison of models on different catchments show that, apart from calibration that often requires a long phase of measurements, it remains hazardous to use these models in order to predict soil losses on the scale of a non-equipped catchment [JET 99].

As for water erosion, several physically based wind erosion models have been developed, for example the Wind Erosion Prediction System (WEPS),

5 Available at fargo.nserl.purdue.edu/rusle2_dataweb/About_RUSLE2_Technology. htm.
6 Available at www.tucson.ars.ag.gov/kineros/.
7 Available at www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosion-research /docs/wepp/research.

which includes many parameters[8] [WAG 13], and has the same flaws as water erosion models of the same type. For more than 20 years, modeling efforts have been made to provide an increasingly detailed description of processes [SHA 08] and furthermore, to offer simple versions, taking into account a limited number of input parameters, if possible derived from satellite observations, that are usable from a local to a global scale and can therefore be integrated, for example, in global climate models [MAR 14].

3.5.3. *Hybrid models*

Hybrid models combine knowledge of processes and statistical approaches. Thus, expert systems can predict runoff from surface conditions (see Chapter 2) and erosion based on surface crusting, roughness and other classes of parameters that are simple to obtain in the field [CER 02] or by remote sensing [KIN 05], thus allowing an assessment of water erosion risks on the scale of a country such as France [LEB 02].

3.6. Principles of soil conservation

Soil conservation principles are derived from knowledge and factors of erosion processes. These are divided into two main scales: the field and the catchment.

3.6.1. *Field level: limiting detachment*

3.6.1.1. *Increasing structural stability: amending the soil*

The objective is to reduce soil erodibility (K) by increasing its resistance to disintegration, and thus increasing its structural stability (see Chapter 2). This generally involves increasing its organic carbon content: manure, sewage sludge (with risks of pollution, see Chapters 6 and 7), compost, and organic waste products in general (see Chapter 9). Liming (the addition of calcium or calcium–magnesium amendments) also tends to improve the soil's resistance to crusting, and therefore to runoff and erosion [AND 07a].

8 Available at https://infosys.ars.usda.gov/WindErosion/weps/wepshome.html.

3.6.1.2. *Reducing the kinetic energy received: maintaining surface cover*

As already indicated in Chapter 2 (section 2.3.4), it is the vegetation closest to the ground that best protects it from the impact of drops. In this respect, crop residues can be very effective (Figure 3.9; see section 3.3.2 on factor C above). If a tree cover is devoid of undergrowth, it will have no protective effect and may even increase the risk of erosion [RIB 17] by increasing the median size of the through flow drops that will have crossed its cover.

Soils that are less sensitive to surface crusts and are cloddier will also offer better resistance to wind erosion.

3.6.1.3. *Reducing runoff velocity t: reducing slope and plot length*

Controlling runoff velocity is important in order to limit the risk of rills and gullies. Since at least the Bronze Age, farmers have sought to reduce slope inclination (S factor) through the construction of terraces [WEI 16] or contour benches. It is especially in conditions of high population density – and therefore abundant labor – that terraces were built to combat erosion: Asia, Mediterranean countries and Andes (Figure 3.17). Not only do they require a considerable construction effort, whether manual or mechanical, but they also require constant maintenance. Their abandonment, following the rural exodus in southern Europe, thus leads to a very marked erosion in gullies. Runoff velocity may also be reduced by contour stone bunds [ZOU 14].

With increased plot size, mechanized tillage has enhanced the risk of erosion. Indeed, the longer a field is, the higher the wind speeds on the ground and runoff will be, and therefore, the higher the risks of wind erosion [GIL 96] and gully erosion [VAL 05] will be. Plots of limited size also tend to reduce agricultural erosion [NPV 00].

Figure 3.17. *Example of several simultaneous soil conservation practices: terraces, small plots, alternating crops in space and time (rotations), agroforestry and windbreak trees, Isla del Sol, Lake Titicaca, Bolivia (photo: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

3.6.1.4. *Reducing wind speed: increasing surface roughness*

As shown above in the study of wind erosion processes, it is only from a wind velocity threshold that grains with a diameter of around 100 µm begin to erode. The reduction of wind speed on the ground thus limits the risks of wind erosion. One of the most common practices is to plant windbreak hedges or other forms of obstacles such as small braided straw palisades (Figure 3.18) [WAN 15].

However, as with water erosion, it is soil surface cover that is the most effective [ABD 11]. Thus, the Sahel rangelands show much less wind erosion than the Sahara or the cultivated fields of the southern Sahel [PIE 15]. The positive effect of crop residues on soil protection is even more marked than for water erosion (see Figure 3.9), since 2% of the soil covered with millet stalks (about 100 kg ha^{-1}) significantly reduces wind erosion compared to bare soil [ABD 11].

Figure 3.18. *Wind erosion control methods to protect the road that crosses the 446 km of dunes of the Taklamakan Desert, Xinjiang, China: a strip of reed straw checkerboards (C), about 50 m wide, precedes at least six lines of hedges (H) irrigated from the water table and composed of several species adapted to desert conditions and salt water [CHE 15] (photos: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip*

3.6.1.5. *Avoiding soil crumbling: reducing soil tillage and cattle trampling*

Any form of soil fragmentation encourages soil erosion. It is thus preferable to avoid any tillage on steep slopes in order to avoid tillage erosion. Besides, tillage preparation is often accompanied by the production of small aggregates, which are more prone to surface crusting than larger clods (see Chapter 2). On sandy soils, surface crusts that develop after tillage do not reduce wind erosion [RAJ 03]. Soil tillage, whether manual or mechanical, as well as cattle trampling tend to break up the soil in dry conditions [HIE 99], and therefore encourage the dust emission during windy periods.

This is how less tillage-based agricultural practices were developed, notably after the great wind erosion crisis in the United States in the mid-1930s (the "dust bowl" decade). In particular, conservation agriculture was adopted that, despite many variations, is based on three main principles [FRI 12]:

– direct seeding and very low tillage;

– permanent soil cover, including crop residues;

– rotations in space and time, including legumes.

As a result, these principles combine those mentioned above and allow a significant reduction in soil losses. However, a cropping system cannot be solely assessed on the basis of soil conservation. Several criticisms have been expressed, notably on the difficulty of adopting this type of practice by family farming in Africa [GIL 09]. It is indeed necessary to have specialized tools to sow through a mulch, in addition to the reliance on synthetic herbicides whose harmlessness for man and the environment is called into question. Moreover, the best carbon storage in soils is due more to the addition of organic matter than to non-tillage [DER 10, VIR 12].

3.6.2. *Catchment scale: slowing runoff and promoting deposition*

On the catchment scale, it is necessary to take all erosive processes into account. Soil conservation measures should give priority to the protection of upstream areas that are likely to generate runoff by applying the principles above (see section 3.6.1). A landscape mosaic comprising forest or grassed plots reduces the speed of runoff (see section 3.6.1.3) and traps sediment on the slopes [GUM 11, VAL 99]. Once rills or gullies have formed, it is important to install obstacles likely to retain sediments: fascines, logs (Figure 3.19), gabions, and even check dams starting downstream from a threshold (rock outcrop), since this form of erosion is regressive, in other words, it progresses from downstream to upstream.

Figure 3.19. *Methods to control concentrated erosion. On the left: a series of fascines (F) retain sediments from a channel (R), Zamok Park, Lviv, Ukraine. On the right: logs (L) were installed across a small rill (G) formed from a path in the beech forest, Chojnik, Poland (photos: C. Valentin). For a color version of this figure, see www.iste.co.uk/valentin/soils5.zip.*

Hydrological connectivity must be counteracted by multiplying obstacles to flow along contour banks: hedges, contour drainage ditches.

For mass movements (see section 3.3.4), priority must be given to mapping and preventing areas at risk, in particular by avoiding building there. In areas with steep slopes where landslides have not yet occurred, certain signs may indicate these risks: head scarps and cracked walls. In principle, planting trees with deep taproots helps to stabilize the slopes. Terrace construction can also be an effective method, as can be the lowering of the water table, which reduces soil moisture and thus soil mass. Interventions can therefore affect several elements of the critical zone, from vegetation to water tables.

3.7. Population density, economic contexts and public policies

There is a fairly good global correspondence between low population density, economic development and soil conservation [ALM 15]. The island of Hispaniola, which is divided into two states – Haiti and the Dominican Republic – illustrates this relationship, showing a very strong contrast of erosion on both sides of the border [WIL 01]. In Haiti, with a very high density in rural areas (885 inhabitants per km^2 of arable land) associated with a gross national product (GNP) per capita of US$730, soils are very severely eroded. In the Dominican Republic, a density that is four times lower (221 inhabitants per km^{-2} of arable land) and almost ten times higher GNP per capita (US$6,910), as well as an environmental conservation and national park development policy, have allowed the development of protected areas on nearly one-third of the territory [WIL 01].

However, there are many exceptions to this rule. For example, in the Mandara Mountains in northern Cameroon, despite a population density of 200 inhabitant per km^{-2}, communities have acquired strong control over the construction and maintenance of terraces and management of organic fertilizers. It is the same on the island of Java in Indonesia, where rural populations can exceed 600 inhabitants per km^2. They have adopted anti-erosive measures, particularly based on the use of organic waste (manure, compost, etc.). It is therefore not always the poorest communities that degrade the soil the most. Of five agricultural catchments in Southeast Asia, Thailand has the highest soil losses, with the least rainfall and the highest income for farmers [VAL 08].

In the absence of regulations on soil protection in Europe, it is the Water Framework Directive that indirectly promotes soil conservation practices. In order to reduce nitrate levels in water tables, some of the rules that must be respected in the zones, defined as vulnerable, contribute to the fight against erosion. On a plot scale, it is now mandatory to install soil cover in these areas in order to limit nitrogen leaching during rainy periods. These are usually catch crops, often referred to in France by their acronym CIPAN (*Culture Intermédiaire Piège A Nitrates*), such as white mustard or alfalfa, which can then be used as green manure. On the catchment scale, vegetated strips that are at least 5 or 10 m wide depending on the region must now be established along waterways, which makes it possible to retain part of the sediment.

However, some public soil conservation policies may have the opposite effect to that expected. Thus, the desire to preserve the forest in Laos and to reduce, in each village, the areas accessible for cultivation has led to a very strong local increase in population density, which in turn led to a reduction or even disappearance of the fallow period, and a strong increase in erosion [LES 12, VAL 08]. Similarly, a public policy for encouraging the planting of teak trees, unaccompanied by training farmers in forest practices (maintenance of undergrowth, fire control, appropriate density, reasoned thinning), has caused a sharp increase in erosion compared with rainfed rice cultivation [RIB 17].

The volume in this series *Soils as a Key Component of the Critical Zone 2: Societal Issues* discusses public policy issues concerning soils and their protection.

3.8. Conclusions

Soil erosion results from many factors and processes that need to be considered at different scales of space and time. Only by identifying these multiple factors and processes can soil conservation strategies be designed. Consequently, they can only very rarely be based on a single approach.

Although the various erosive processes have many points in common (detachment, transport, deposition) and similar issues (origin of sediments, distance of transfers, residence time, etc.), they require diverse study methods, skills and modeling approaches.

Accelerated erosion is one of the major causes of soil degradation, but also the consequence of other forms of environmental degradation: deforestation, reduction of soil organic matter levels, compaction by agricultural and forestry machinery as a result of land use change and increase in the frequency of extreme events as a result of climate change.

It is also a symptom of dysfunctional agricultural, pastoral, forestry, mining and public work practices. This symptom should alert the different stakeholders in order to make a more general diagnosis on the sustainability of their environmental management systems. These stakeholders must be involved in defining soil conservation strategies. Many failures result from the neglect to take their objectives and constraints into account. These strategies must be included in broader policies. Moreover, it is often policies relating to the protection of other components of the critical zone (water and forest cover) that have positive consequences on soil conservation. The international 4 per 1000 initiative, which aims to increase atmospheric carbon storage in soils to combat climate disturbances, should promote soil conservation, given that the recommended practices (soil cover, hedges, grasslands, rotations, etc.) are identical to those described above.

As many success stories have shown, such as the significant reduction in sediment levels in Mississippi as a result of changes in cropping practices, accelerated erosion is not inevitable when there is the will and the means to reduce it.

RESEARCH QUESTIONS.–

1) What are the origins and causes (factors and processes) of sediment production at the outlet of catchment and of dust emission?

2) How can erosion predicting models be better constrained by relatively simple indicators or markers?

3) What are the consequences of erosion on soil, water and air quality, and on human and animal health?

RECOMMENDATIONS.–

1) Always specify the measurement scale when using erosion data and the nature of the erosion considered (particulate, soluble).

2) Combine several soil conservation principles based on the identification of processes and dominant factors in a given context, rather than applying a “universal” recipe.

3) Involve the various stakeholders (farmers and other land managers, public authorities, etc.) in the definition of anti-erosive strategies that must be well thought out on several scales (at least plots and catchments) in the context of public policies.

3.9. References

[ABD 11] ABDOURHAMANE TOURE A., RAJOT J.L., GARBA Z. *et al.*, “Impact of very low crop residues cover on wind erosion in the Sahel”, *Catena*, vol. 85, pp. 205–214, 2011.

[ACK 16] ACKERER J., CHABAUX F., VAN DER WOERD J. *et al.*, “Regolith evolution on the millennial timescale from combined U–Th–Ra isotopes and in situ cosmogenic ^{10}Be analysis in a weathering profile (Strengbach catchment, France)”, *Earth and Planetary Science Letters*, vol. 453, pp. 33–43, 2016.

[ALM 15] AL-MULALI U., WENG-WAI C., SHEAU-TING, L. *et al.*, “Investigating the environmental Kuznets curve (EKC) hypothesis by utilizing the ecological footprint as an indicator of environmental degradation”, *Ecological Indicators*, vol. 48, pp. 315–323, 2015.

[ALT 12] ALTHUWAYNEE O.F., PRADHAN B., LEE S., “Application of an evidential belief function model in landslide susceptibility mapping”, *Computers & Geosciences*, vol. 44, pp. 120–135, 2012.

[ALV 12] ALVAREZ-COBELAS M., ANGELER D.G., SÁNCHEZ-CARRILLO S. *et al.*, "A worldwide view of organic carbon export from catchments", *Biogeochemistry*, vol. 107, nos 1–3, pp. 275–293, 2012.

[AND 07a] ANDRY H., YAMAMOTO T., INOUE M., "Effectiveness of hydrated lime and artificial zeolite amendments and sedum (*Sedum sediforme*) plant cover in controlling soil erosion from an acid soil", *Soil Research*, vol. 45, no. 4, pp. 266–279, 2007.

[AND 07b] ANDERSON S.P., VON BLANCKENBURG F., WHITE A.F., "Physical and chemical controls on the critical zone", *Elements*, vol. 3, no. 5, pp. 315–319, 2007.

[ANN 16] ANNANDALE G.W., GREGORY L.M., KARKI P., *Extending the Life of Reservoirs*, World Bank Publications, Washington, D.C., 2016.

[ARA 08] ARABI M., FRANKENBERGER J.R., ENGEL B.A. *et al.*, "Representation of agricultural conservation practices with SWAT", *Hydrological Processes*, vol. 22, no. 16, pp. 3042–3055, 2008.

[BER 17] BERGAMETTI G., MARTICORENA B., RAJOT J.L. *et al.*, "Dust uplift potential in Central Sahel: an analysis based on 10 years of meteorological measurements at high temporal resolution", *Journal of Geophysical Research,* vol. 122, no. 12, pp. 433–12, 2017.

[BLA 00] BLASCHKE P.M., TRUSTRUM N.A., HICKS D.L., "Impacts of mass movement erosion on land productivity: a review", *Progress in Physical Geography*, vol. 24, no. 1, pp. 21–52, 2000.

[BOR 16] BORRELLI P., PANAGOS P., BALLABIO C. *et al.*, "Towards a Pan-European assessment of land susceptibility to wind erosion", *Land Degradation & Development*, vol. 27, no. 4, pp. 1 093–1 105, 2016.

[CER 02] CERDAN O., SOUCHÈRE V., LECOMTE V. *et al.*, "Incorporating soil surface crusting processes in an expert-based runoff model: Sealing and Transfer by Runoff and Erosion related to Agricultural Management", *Catena*, vol. 46, no. 2, pp. 189–205, 2002.

[CHA 05a] CHAPLOT V., GIBOIRE G., MARCHAND P. *et al.*, "Dynamic modelling for linear erosion initiation and development under climate and land-use changes in northern Laos", *Catena*, vol. 63, no. 2, pp. 318–328, 2005.

[CHA 05b] CHAPLOT V., LE BROZEC E.C., SILVERA N. *et al.*, "Spatial and temporal assessment of linear erosion in catchments under sloping lands of northern Laos", *Catena*, vol. 63, no. 2, pp. 167–184, 2005.

[CHA 15] CHAPPELL A., BALDOCK J., SANDERMAN J., "The global significance of omitting soil erosion from soil organic carbon cycling schemes", *Nature Climate Change,* vol. 6, pp. 187–191, 2015.

[CHA 93] CHAPERON P., DANLOUX J., FERRY L., *Fleuves et rivières de Madagascar*, ORSTOM, Paris, available at: http://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_7/b_fdi_03_03/37307.pdf, 1993.

[CHE 15] CHENG H., HE J., XU X. *et al.*, "Blown sand motion within the sand-control system in the southern section of the Taklimakan Desert Highway", *Journal of Arid Land*, vol. 7, no. 5, pp. 599–611, 2015.

[COL 84] COLLINET J., VALENTIN C., "Evaluation of factors influencing water erosion in West Africa using rainfall simulation", *Challenges in African Hydrology and Water Resources*, IAHS Press, Wallingford, pp. 451–461, 1984.

[COX 10] COX R., ZENTNER D.B., RAKOTONDRAZAFY A.F.M. *et al.*, "Shakedown in Madagascar: occurrence of lavakas (erosional gullies) associated with seismic activity", *Geology*, vol. 38, no. 2, pp. 179–182, 2010.

[DEL 15] DELLINGER M., BOUCHEZ J., GAILLARDET J. *et al.*, "Testing the steady state assumption for the Earth's surface denudation using Li Isotopes in the Amazon Basin", *Procedia Earth and Planetary Science*, vol. 13, pp. 162–168, 2015.

[DEN 03] DEN BIGGELAAR C., LAL R., WIEBE K. *et al.*, "The global impact of soil erosion on productivity: I: absolute and relative erosion-induced yield losses", *Advances in Agronomy*, vol. 81, pp. 1–48, 2003.

[DER 10] DE ROUW A., HUON S., SOULILEUTH B. *et al.*, "Possibilities of carbon and nitrogen sequestration under conventional tillage and no-till cover crop farming (Mekong valley, Laos)", *Agriculture, Ecosystems & Environment*, vol. 136, no. 1, pp. 148–161, 2010.

[DIA 05] DIAMOND J., *Collapse: How Societies Choose to Fail or Succeed*, Viking Penguin, London, 2005.

[DUP 09] DUPIN B., DE ROUW A., PHANTAHVONG K.B. *et al.*, "Assessment of tillage erosion rates on steep slopes in northern Laos", *Soil and Tillage Research*, vol. 103, no. 1, pp. 119–126, 2009.

[DUP 15] DUPAS R., GASCUEL-ODOUX C., GILLIET N. *et al.*, "Distinct export dynamics for dissolved and particulate phosphorus reveal independent transport mechanisms in an arable headwater catchment", *Hydrological Processes*, vol. 29, pp. 3162–3178, 2015.

[EVR 16] EVRARD O., LACEBY J.P., HUON S. *et al.*, "Combining multiple fallout radionuclides (^{137}Cs, ^{7}Be, ^{210}Pbxs) to investigate temporal sediment source dynamics in tropical, ephemeral riverine systems", *Journal of Soils and Sediments*, vol. 16, no. 3, pp. 1130–1144, 2016.

[FAO 15] FAO, Status of the world's soil resources, Main report, Rome, available at: http://www.fao.org/3/a-i5199e.pdf, 2015.

[FLA 07] FLANAGAN D.C., GILLEY J.E., FRANTI T.G., "Water Erosion Prediction Project (WEPP): development history, model capabilities, and future enhancements", *Transactions of the ASABE,* vol. 50, no. 5, pp. 1603–1612, 2007.

[FOU 14] FOUCHER A., SALVADOR-BLANES S., EVRARD O. *et al.*, "Increase in soil erosion after agricultural intensification: evidence from a lowland basin in France", *Anthropocene*, vol. 7, pp. 30–41, 2014.

[FOX 07] FOX G.A., WILSON G.V., SIMON A. *et al.*, "Measuring streambank erosion due to ground water seepage: correlation to bank pore water pressure, precipitation and stream stage", *Earth Surface Processes and Landforms*, vol. 32, no. 10, pp. 1558–1573, 2007.

[FRI 12] FRIEDRICH T., DERPSCH R., KASSAM A., "Overview of the global spread of conservation agriculture", *Field Actions Science Reports*, special edition, no. 6, available at: http://factsreports.revues.org/1941, 2012.

[FRO 16] FROEHLICHER L., SCHWARTZ D., ERTLEN D. *et al.*, "Hedges, colluvium and lynchets along a reference toposequence (Habsheim, Alsace, France): history of erosion in a lœss area", *Quaternaire. Revue de l'Association française pour l'étude du Quaternaire*, vol. 27, no. 2, pp. 173–185, 2016.

[FRY 01] FRYREAR D.W., CHEN W.N., LESTER C., "Revised wind erosion equation", *Annals of Arid Zone*, vol. 40, no. 3, pp. 265–279, 2001.

[FRY 12] FRY J.J., VOGEL A., ROYET P. *et al.*, "Dam failures by erosion: lessons from ERINOH data bases", *ICSE6 Paris*, pp. 273–280, August 27–31, 2012.

[FRY 86] FRYREAR D.W., "A field dust sampler", *Journal of Soil and Water Conservation*, vol. 41, no. 2, pp. 117–120, 1986.

[GAB 03] GABRIELS D., GHEKIERE G., SCHIETTECATTE W. *et al.*, "Assessment of USLE cover-management C-factors for 40 crop rotation systems on arable farms in the Kemmelbeek watershed, Belgium", *Soil and Tillage Research*, vol. 74, no. 1, pp. 47–53, 2003.

[GAR 15] GARCÍA-RUIZ J.M., BEGUERÍA S., NADAL-ROMERO E. *et al.*, "Meta-analysis of soil erosion rates across the world", *Geomorphology*, vol. 239, pp. 160–173, 2015.

[GIL 09] GILLER K.E., WITTER E., CORBEELS M. *et al.*, "Conservation agriculture and smallholder farming in Africa: the heretics' view", *Field Crops Research*, vol. 114, no. 1, pp. 23–34, 2009.

[GIL 72] GILLETTE D.A., BLIFFORD JR I.H., FENSTER C.R., "Measurements of aerosol size distributions and vertical fluxes of aerosols on land subject to wind erosion", *Journal of Applied Meteorology*, vol. 11, no. 6, pp. 977–987, 1972.

[GIL 77] GILLETTE D.A., "Fine particulate emissions due to wind erosion", *Transactions of the ASAE*, vol. 20, no. 5, pp. 890–897, 1977.

[GIL 96] GILLETTE D.A., HERBERT G., STOCKTON P.H. *et al.*, "Causes of the fetch effect in wind erosion", *Earth Surface Processes and Landforms*, vol. 21, no. 7, pp. 641–659, 1996.

[GIN 12] GINOUX P., PROSPERO J.M., GILL T.E. *et al.*, "Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products", *Reviews of Geophysics*, vol. 50, no. 3, pp. 1–36, 2012.

[GOS 08] GOOSSENS D., RAJOT J.L., "Techniques to measure the dry aeolian deposition of dust in arid and semi-arid landscapes: a comparative study in West Niger", *Earth Surface Processes and Landforms*, vol. 33, no. 2, pp. 178–195, 2008.

[GRE 12] GRELLIER S., KEMP J., JANEAU J.L. *et al.*, "The indirect impact of encroaching trees on gully extension: a 64 year study in a sub-humid grassland of South Africa", *Catena*, vol. 98, pp. 110–119, 2012.

[GUM 11] GUMIERE S.J., LE BISSONNAIS Y., RACLOT D. *et al.*, "Vegetated filter effects on sedimentological connectivity of agricultural catchments in erosion modeling: a review", *Earth Surface Processes and Landforms*, vol. 36, no. 1, pp. 3–19, 2011.

[HAD 13] HADDADCHI A., RYDER D.S., EVRARD O. *et al.*, "Sediment fingerprinting in fluvial systems: review of tracers, sediment sources and mixing models", *International Journal of Sediment Research*, vol. 28, no. 4, pp. 560–578, 2013.

[HIE 99] HIERNAUX P., BIELDERS C.L., VALENTIN C. *et al.*, "Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands", *Journal of Arid Environments*, vol. 41, no. 3, pp. 231–245, 1999.

[HOF 15] HOFFMANN T., PENNY D., STINCHCOMB G. *et al.*, "Global soil and sediment transfers in the Anthropocene", *PAGES Magazine*, vol. 23, pp. 37, 2015.

[HUO 13] HUON S., DE ROUW A., BONTÉ P. *et al.*, "Long-term soil carbon loss and accumulation in a catchment following the conversion of forest to arable land in northern Laos", *Agriculture, Ecosystems & Environment*, vol. 169, pp. 43–57, 2013.

[HUO 17] HUON S., EVRARD O., GOURDIN E. *et al.*, "Suspended sediment source and propagation during monsoon events across nested sub-catchments with contrasted land uses in Laos", *Journal of Hydrology: Regional Studies*, vol. 9, pp. 69–84, 2017.

[JET 99] JETTEN V., DE ROO A.D., FAVIS-MORTLOCK D., "Evaluation of field-scale and catchment-scale soil erosion models", *Catena*, vol. 37, no. 3, pp. 521–541, 1999.

[KIM 17] KIM J.H., FOURCAUD T., JOURDAN C. *et al.*, "Vegetation drives slope stability and its variability through hydrological impacts", *Geophysical Research Letters*, vol. 44, pp. 4897–4907, 2017.

[KIN 05] KING C., BAGHDADI N., LECOMTE V. *et al.*, "The application of remote-sensing data to monitoring and modelling of soil erosion", *Catena*, vol. 62, no. 2, pp. 79–93, 2005.

[KLE 11] KLEINMAN P., SHARPLEY A., BUDA A. *et al.*, "Soil controls of phosphorus in runoff: management barriers and opportunities", *Canadian Journal of Soil Science*, vol. 91, vol. 3, pp. 329–338, 2011.

[LEB 02] LE BISSONNAIS Y., MONTIER C., JAMAGNE M. *et al.*, "Mapping erosion risk for cultivated soil in France", *Catena*, vol. 46, vol. 2, pp. 207–220, 2002.

[LES 12] LESTRELIN G., VIGIAK O., PELLETREAU A. *et al.*, "Challenging established narratives on soil erosion and shifting cultivation in Laos", *Natural Resources Forum,* vol. 36, no. 2, pp. 63–75, 2012.

[LOG 13] LOGSDON S.D., "Depth dependence of chisel plow tillage erosion", *Soil and Tillage Research*, vol. 128, pp. 119–124, 2013.

[MAR 10] MARTICORENA B., CHATENET B., RAJOT J.L. *et al.*, "Temporal variability of mineral dust concentrations over West Africa: analyses of a pluriannual monitoring from the AMMA Sahelian Dust Transect", *Atmospheric Chemistry and Physics*, vol. 10, pp. 8899–8915, 2010.

[MAR 14] MARTICORENA B., "Dust production mechanisms", in KNIPPERTZ P., STUUT J.-B.W. (eds), *Mineral Dust: A Key Player in the Earth System*, Springer, Dordrecht, pp. 93–120, 2014.

[MAR 17] MARTICORENA B., CHATENET B., RAJOT J.L. *et al.*, "Mineral dust over west and central Sahel: Seasonal patterns of dry and wet deposition fluxes from a pluriannual sampling (2006–2012)", *Journal of Geophysical Research: Atmospheres*, vol. 122, no. 2, pp. 1338–1364, 2017.

[MON 07a] MONTGOMERY D.R., *Dirt: The Erosion of Civilizations*, University of California Press, Berkeley, CA, 2007.

[MON 07b] MONTGOMERY D.R., "Soil erosion and agricultural sustainability", *Proceedings of the National Academy of Sciences*, vol. 104, no. 33, pp. 13268–13272, 2007.

[MON 12] MONA L., LIU Z., MÜLLER D. *et al.*, "Lidar measurements for desert dust characterization: an overview", *Advances in Meteorology*, available at: http://dx.doi.org/10.1155/2012/356265, 2012.

[MOR 98] MORGAN R.P.C., QUINTON J.N., SMITH R.E. *et al.*, "The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments", *Earth Surface Processes and Landforms*, vol. 23, no. 6, pp. 527–544, 1998.

[MUH 14] MUHS D.R., PROSPERO J.M., BADDOCK M.C. *et al.*, "Identifying sources of aeolian mineral dust: present and past", in KNIPPERTZ P., STUUT J.-B.W. (eds), *Mineral Dust: A Key Player in the Earth System*, Springer, Dordrecht, pp. 51–74, 2014.

[NAS 04] NASRI S., CUDENNEC C., ALBERGEL J. *et al.*, "Use of a geomorphological transfer function to model design floods in small hillside catchments in semiarid Tunisia", *Journal of Hydrology*, vol. 287, no. 1, pp. 197–213, 2004.

[NIX 04] NIXON S., "The Artificial Nile. The Aswan High Dam blocked and diverted nutrients and destroyed a Mediterranean fishery, but human activities may have revived it", *American Scientist*, vol. 92, no. 2, pp. 158–164, 2004.

[OLD 91] OLDEMAN L.R., HAKKELING R.T.A., SOMBROCK W.G., *Global Assessment of Soil Degradation (GLASOD), World map of the status of human-induced soil degradation*, ISRIC, Wageningen, the Netherlands, available at: http://www.isric.org/projects/global-assessment-human-induced-soil-degradation-glasod, 1991.

[PAN 14] PANAGOS P., MEUSBURGER K., BALLABIO C. *et al.*, "Soil erodibility in Europe: a high-resolution dataset based on LUCAS", *Science of the Total Environment*, vol. 479, pp. 189–200, 2014.

[PAN 15a] PANAGOS P., BALLABIO C., BORRELLI P. *et al.*, "Rainfall erosivity in Europe", *Science of the Total Environment*, vol. 511, pp. 801–814, 2015.

[PAN 15b] PANAGOS P., BORRELLI P., MEUSBURGER K. *et al.*, "Estimating the soil erosion cover-management factor at the European scale", *Land Use Policy*, vol. 48, pp. 38–50, 2015.

[PAN 95] PANINGBATAN E.P., CIESIOLKA C.A., COUGHLAN K.J. *et al.*, "Alley cropping for managing soil erosion of hilly lands in the Philippines", *Soil Technology*, vol. 8, no. 3, pp. 193–204, 1995.

[PAU 16] PAULA D.T.D., MARTINS FILHO M.V., FARIAS V.L. *et al.*, "Clay and phosphorus losses by erosion in oxisol with sugarcane residues", *Engenharia Agrícola*, vol. 36, no. 6, pp. 1063–1072, 2016.

[PIE 15] PIERRE C., KERGOAT L., BERGAMETTI G. *et al.*, "Modeling vegetation and wind erosion from a millet field and from a rangeland: two Sahelian case studies", *Aeolian Research*, vol. 19, pp. 97–111, 2015.

[POD 08] PODWOJEWSKI P., ORANGE D., JOUQUET P. *et al.*, "Land-use impacts on surface runoff and soil detachment within agricultural sloping lands in Northern Vietnam", *Catena*, vol. 74, no. 2, pp. 109–118, 2008.

[POE 03] POESEN J., NACHTERGAELE J., VERSTRAETEN G. *et al.*, "Gully erosion and environmental change: importance and research needs", *Catena*, vol. 50, no. 2, pp. 91–133, 2003.

[PYE 95] PYE K., "The nature, origin and accumulation of lœss", *Quaternary Science Reviews*, vol. 14, no. 7, pp. 653–667, 1995.

[QUI 10] QUINTON J.N., GOVERS G., VAN OOST K. *et al.*, "The impact of agricultural soil erosion on biogeochemical cycling", *Nature Geoscience*, vol. 3, no. 5, pp. 311–314, 2010.

[RAJ 03] RAJOT J.L., ALFARO S.C., GOMES L. *et al.*, "Soil crusting on sandy soils and its influence on wind erosion", *Catena*, vol. 53, no. 1, pp. 1–16, 2003.

[RIB 11] RIBOLZI O., PATIN J., BRESSON L.M. *et al.*, "Impact of slope gradient on soil surface features and infiltration on steep slopes in northern Laos", *Geomorphology*, vol. 127, no. 1, pp. 53–63, 2011.

[RIB 17] RIBOLZI O., EVRARD O., HUON S. *et al.*, "From shifting cultivation to teak plantation: effect on overland flow and sediment yield in a montane tropical catchment", *Scientific Reports, Nature*, vol. 7, pp. 3987, 2017.

[ROC 16] ROCHELLE-NEWALL E.J., RIBOLZI O., VIGUIER M. *et al.*, "Effect of land use and hydrological processes on *Escherichia coli* concentrations in streams of tropical, humid headwater catchments", *Scientific Reports*, *Nature*, vol. 6, pp. 1–12, 2016.

[RUM 06] RUMPEL C., CHAPLOT V., PLANCHON O. *et al.*, "Preferential erosion of black carbon on steep slopes with slash and burn agriculture", *Catena*, vol. 65, no. 1, pp. 30–40, 2006.

[SAB 14] SABATIER P., POULENARD J., FANGET B. *et al.*, "Long-term relationships among pesticide applications, mobility, and soil erosion in a vineyard watershed", *Proceedings of the National Academy of Sciences*, vol. 111, no. 44, pp. 15647–15652, 2014.

[SHA 08] SHAO Y., *Physics and Modelling of Wind Erosion*, Springer Science & Business Media, New York, 2008.

[SIM 95] SIMONSON R.W., "Airborne dust and its significance to soils", *Geoderma*, vol. 65, nos 1–2, pp. 1–43, 1995.

[SMI 95] SMITH R.E., GOODRICH D.C., WOOLHISER D.A. *et al.*, "KINEROS–a kinematic runoff and erosion model", *Computer Models of Watershed Hydrology*, vol. 20, pp. 627–668, 1995.

[STO 14] STOCKMANN U., MINASNY B., MCBRATNEY A.B., "How fast does soil grow?", *Geoderma*, vol. 216, pp. 48–61, 2014.

[TEG 14] TEGEN I., SCHULZ M., "Numerical dust models", in KNIPPERT P., STUUT J.-B.W. (eds), *Mineral Dust: A Key Player in the Earth System*, Springer, Dordrecht, pp. 201–222, 2014.

[TIN 12] TING-HSUAN HUANG, YU-HAN FU, PEI-YI PAN, *et al.*, "Fluvial carbon fluxes in tropical rivers", *Current Opinion in Environmental Sustainability,* vol. 4, no. 2, pp. 162–169, 2012.

[TOD 07] TODD M.C., WASHINGTON R., MARTINS J.V. *et al.*, "Mineral dust emission from the Bodélé Depression, northern Chad, during BoDEx 2005", *Journal of Geophysical Research: Atmospheres*, vol. 112, no. D6, 2007.

[VAL 05] VALENTIN C., POESEN J., LI Y., "Gully erosion: impacts, factors and control", *Catena*, vol. 63, no. 2, pp. 132–153, 2005.

[VAL 99] VALENTIN C, D'HERBÈS J.M., POESEN J., "Soil and water components of banded vegetation patterns", *Catena*, vol. 37, pp. 1–24, 1999.

[VAL 08] VALENTIN C., AGUS F., ALAMBAN R. *et al.*, "Runoff and sediment losses from 27 upland catchments in Southeast Asia: impact of rapid land use changes and conservation practices", *Agriculture, Ecosystems & Environment*, vol. 128, no. 4, pp. 225–238, 2008.

[VAN 00] VAN OOST K., GOVERS G., DESMET P., "Evaluating the effects of changes in landscape structure on soil erosion by water and tillage", *Landscape Ecology*, vol. 15, no. 6, pp. 577–589, 2000.

[VIR 12] VIRTO I., BARRÉ P., BURLOT A. *et al.*, "Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems", *Biogeochemistry*, vol. 108, no. 1, pp. 17–26, 2012.

[VOE 13] VOEPEL H., SCHUMER R., HASSAN M.A., "Sediment residence time distributions: theory and application from bed elevation measurements", *Journal of Geophysical Research: Earth Surface*, vol. 118, pp. 2557–2567, 2013.

[WAG 13] WAGNER L.E., "A history of wind erosion prediction models in the United States Department of Agriculture: The Wind Erosion Prediction System (WEPS)", *Aeolian Research*, vol. 10, pp. 9–24, 2013.

[WAL 13] WALLING D.E., "The evolution of sediment source fingerprinting investigations in fluvial systems", *Journal of soils and sediments*, vol. 13, no. 10, pp. 1658–1675, 2013.

[WAN 13] WANG B., ZHENG F., RÖMKENS M.J. *et al.*, "Soil erodibility for water erosion: a perspective and Chinese experiences", *Geomorphology*, vol. 187, pp. 1–10, 2013.

[WAN 15] WANG T., XUE X., ZHOU L. *et al.*, "Combating aeolian desertification in northern China", *Land Degradation & Development*, vol. 26, no. 2, pp. 118–132, 2015.

[WEB 12] WEBB N.P., CHAPPELL A., STRONG C.L. *et al.*, "The significance of carbon-enriched dust for global carbon accounting", *Global Change Biology*, vol. 18, no. 11, pp. 3275–3278, 2012.

[WEI 16] WEI W., CHEN D., WANG L. *et al.*, "Global synthesis of the classifications, distributions, benefits and issues of terracing", *Earth-Science Reviews*, vol. 159, pp. 388–403, 2016.

[WIL 01] WILSON J.S., BROTHERS T.S., MARCANO E.J., "Remote sensing of spatial and temporal vegetation dynamics in Hispaniola: a comparison of Haiti and the Dominican Republic", *Geocarto International*, vol. 16, no. 2, pp. 7–18, 2001.

[WIL 80] WILSON S.J., COOKE R.U., "Wind erosion", in KIRKBY M.J., MORGAN R.P.C. (eds), *Soil Erosion*, John Wiley, New York, pp. 217–251, 1980.

[WIS 76] WISCHMEIER W.H., "Use and misuse of the universal soil loss equation", *Journal of Soil and Water Conservation*, vol. 31, pp. 5–9, 1976.

[WIS 78] WISCHMEIER W.H., SMITH D.D., "Predicting rainfall erosion losses – a guide to conservation planning", *Agricultural Handbook*, vol. 537, USDA, WA, available at: https://naldc.nal.usda.gov/download/CAT79706928/PDF, 1978.

[WOO 65] WOODRUFF N.P., SIDDOWAY F.H., "A wind erosion equation", *Soil Science Society of America Journal*, vol. 29, no. 5, pp. 602–608, 1965.

[XUE 93] XUE C., "Historical changes in the Yellow River delta, China", *Marine Geology*, vol. 113, no. 3, pp. 321–330, 1993.

[YU 15] YU H., CHIN M., YUAN T. *et al.*, "The fertilizing role of African dust in the Amazon rainforest: a first multiyear assessment based on data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations", *Geophysical Research Letters*, vol. 42, no. 6, pp. 1984–1991, 2015.

[YU 99] YU B., ROSE C.W., "Application of a physically based soil erosion model, GUEST, in the absence of data on runoff rates: I. Theory and methodology", *Soil Research*, vol. 37, no. 1, pp. 1–12, 1999.

[ZOB 03] ZOBECK T.M., STERK G., FUNK R. *et al.*, "Measurement and data analysis methods for field-scale wind erosion studies and model validation", *Earth Surface Processes and Landforms*, vol. 28, no. 11, pp. 1163–1188, 2003.

[ZOU 14] ZOUGMORÉ R., JALLOH A., TIORO A., "Climate-smart soil water and nutrient management options in semiarid West Africa: a review of evidence and analysis of stone bunds and zaï techniques", *Agriculture & Food Security*, vol. 3, no. 1, pp. 16, 2014.

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