Working Paper
Soil Erosion

Antonio Seoane Dominguez & Ruth Schaldach

> *'The soil is a non-renewable resource that controls the biological, hydrological and geochemical cycles in the Earth System and provides the human societies with goods, services and resources. There is a need to improve the land use practices to obtain a sustainable management and reduce soil erosion risk.'*
> *(Ochoa et al. 2016)*

Abstract

Soil erosion is a geomorphological process that can be caused by nature or human activities. It is found all over the world and the rates at which it occurs are highly variable, depending on climate conditions, topographic circumstances, as well as local soil properties. Most commonly, soil erosion is associated with the impact of water (rainsplash or runoff), but also wind, especially in arid and semi-arid regions. Many studies investigate the effects of soil conservation principles in different regions, showing that there is no single soil conservation principle applicable to all cases. Although soil conservation should always be applied to the specific environment, some local agronomic measures may address all soil disturbances. The application of a vegetation cover has beneficial effects with respect to soil conservation, as it increases soil moisture and organic matter content, further improving the infiltration rates. Furthermore, the use of organic mulch was proven to protect soil against water erosion and improve its physical properties. Whenever possible, agronomic measures should be combined with soil management strategies. Mechanical measures are rather expensive and should be regarded only as additional erosion prevention, but never as a stand-alone approach. There is a high need for governmental action to improve knowledge on soil conservation and apply stronger policies regarding the sustainable use of land.

Keywords: *soil erosion, soil conservation, water erosion, infiltration, land use*

This is a working paper reflecting ongoing work. Comments and suggestions are welcome, please refer them to our discussion forum RUVIVAL Community https://ruvivalcommunity.rz.tuhh.de/c/writers-corner or ruvival@tuhh.de. The final version of this paper will be published as part of RUVIVAL Publication Series (https://www.ruvival.de/reading/). For quotes and citations, please use the final version, or ask for special permission.

Table of Contents

Introduction

A diverse range of key functions is associated with soil. These include food production, storage of organic matter, water and nutrients (thus affecting soil fertility), but also the provision of habitat for a variety of organisms. Nevertheless, soil degradation is occurring globally and its most widespread form is soil erosion (Panagos et al. 2014). Soil erosion is the result of natural geomorphological processes, which are both affected by and have consequences for human activities, often leading to economic and social damage (eds Morgan & Rickson 1994). Particularly accelerated (or human induced) soil erosion can cause catastrophic floods, droughts, desertification, and famines; thus threatening food and environmental security worldwide. The latest Intergovernmental Science-Policy on Biodiversity and Ecosystem Services (IPBES) assessment showed that land degradation caused by human activities is compromising the well-being of 3.2 billion people, driving species extinctions and intensifying global climate change (ed. IPBES 2018). Moreover, they linked land degradation as a major contributor to mass human migration and increased conflict, estimating that 4 billion people will be living in drylands three decades from now (2050 projection). Comparing arable land influenced by human activities with undisturbed forests, the erosion losses from arable land are 70 - 200 higher than in undisturbed forests (Berendse et al. 2015). Zhao et al. (2013) further estimate that about ten million hectares of cultivation area are lost due to soil erosion each year.

Traditionally, soil erosion is associated with agriculture in tropical and semi-arid areas. However, nowadays soil erosion is found globally. A dramatic example is the Loess plateau, located in northwestern China. More than 70 % of the once high, flat plain plateau, has been transformed to a gully-hill dominated region (see Chapter 1) due to massive soil erosion over the last 25 years and intense human activities over the past thousands of years (Fattet et al. 2011). Since the Loess plateau is critical for the Chinese national economic development regarding food and energy production, the livelihood of millions of people who live there is constantly threatened (Zhao et al. 2013). In Europe, intense erosion is widespread in the Mediterranean region (García-Ruiz et al. 2013); above all, vineyards possess the highest erosion rates in Europe compared to other land uses, such as forests, grasslands, shrubs or regeneration (Rodrigo Comino et al. 2015). Panagos et al. (2014) discovered that organic matter has an important impact on soil erodibility (non-resistance of soil to erosion). This is further illustrating that countries with high concentrations of organic matter have the lowest soil erodibility (e.g. Ireland, Estonia, Denmark, the Netherlands, UK, Finland, Sweden, Latvia) in comparison to countries with a low concentration of organic matter (Belgium, Luxembourg, central European countries, Spain, France). Vrieling, Hoedjes & van der Velde (2014) conducted a large-scale analysis of water induced soil erosion in Africa, which shows high values of erodibility in Sub-Saharan countries ranging from West African (Liberia, Ivory Coast, Ghana) to Central African (Cameroon, Dem. Republic of the Congo) and East African countries (South Sudan, Uganda, Ethiopia).

As stated before, soil erosion has a direct, so called on-site effect on agricultural land, lowering food production and food security. Moreover, loss of soil fertility may lead to either an increased expenditure in fertilisers or ultimately to the abandonment of land, resulting in a substantial decline of land value. In addition to this, there are also off-site effects associated with soil erosion. High amounts of sedimentation downstream/downwind can reduce the capacity of rivers and drainage ditches, enhancing the risk of floods, blockage of irrigation canals and decreasing the design life of reservoirs. Besides, sediments (and the chemicals absorbed to them) can increase the levels of nitrogen and phosphorus in rivers and lakes, leading to eutrophication in water bodies. Lastly, previously bound CO_2 may be released into the atmosphere due to the breakdown of soil aggregates, enhancing the atmospheric greenhouse effect (Morgan 2005). The environmental damages mentioned above often involve high economic impacts as well. Annual costs associated with soil erosion in the US sum up to 30 - 44 Billion USD, 90 Million Pounds in the UK and 400 Million USD in Java (Indonesia) alone (Morgan 2005).

There are three main factors that influence the severity of erosion: energy, resistance and protection. Energy involves the potential capability of rainfall, runoff and wind to cause erosion (erosivity). The resistance (or quality) of soil is based on its characteristics regarding erosion (erodibility). For instance, good infiltration indicates for soil of high quality, whereas low infiltration rates deplete the soil's capability to absorb water and sustain plant growth (Zeedyk & Jansens 2006). Lastly, protection refers to the plant cover, as vegetation can reduce soil erosion by intercepting rainfall and reducing the velocity of wind or runoff (eds Morgan & Rickson 1994). With respect to these factors, Morgan (2005) illustrates the main principles for erosion control strategies. These can be summarised as agronomic measures, referring to the use of vegetation to protect soils against erosion; soil management, referring to the preparation of soil to promote plant growth and improve its structure to be more resistant; and, lastly, mechanical methods, referring to engineering structures, such as wind breaks or terraces, to control the flow of water and air.

Erosion Processes & Erosion Measurement

Soil erosion can be defined as the detachment, entrainment and transport of soil particles. The erosive forces leading to these processes can be of anthropogenic (tillage, land levelling, crop harvesting) or natural (rain, runoff, wind, gravity) origin (Martín-Fernández & Martínez-Núñez 2011). Natural soil erosion is divided into water and wind erosion. This chapter will illustrate the basic principles of these two erosion mechanisms.

Soil is principally degraded by water erosion (Ochoa et al. 2016). Thus, understanding the mechanism of water erosion plays an essential role in implementing adequate erosion control strategies (Chapters 2 & 3). The main water erosion processes, which will be further illustrated, include rainsplash erosion, rill and gully erosion and overland flow.

As the name states, rainsplash erosion is caused by the erosive forces of raindrop splashes. Therefore, splash erosion is the first mechanism with respect to the soil erosion process. A detailed image analysis of the splash processes is given in the video 'How water drops impact soil surfaces' produced by the Faculty of Organic Agricultural Sciences from University of Kassel (Reinisch 2015). As a result of the erosive forces of raindrop splashes, soil particles are detached from the soil surface and further transported over short distances. Depending on the soil, splash erosion can displace soil particles as high as 0.6 m vertically and up to 1.5 m horizontally (Jenkins & Alt 2005). Especially on bare soil surfaces, the impact of raindrop splashes is strong. They may enhance soil bulk density due to compacting and crusting, but also shape small craters due to the redistribution of particles, subsequently leading to an increase of the soil surface roughness. The resulting crust may hinder plant establishment since germination and seedling growth are inhibited and infiltration rates are reduced (Fernández-Raga et al. 2017). Reduced infiltration rates on the other hand may produce an accumulation of water on the soil surface. Especially in warm climates, this water will evaporate quickly, thus hindering a potential stock up of underlying aquifers.
The intensity of splash erosion depends on the one hand on the resistance of the soil to erosion and on the other hand on the kinetic energy of the raindrops. Generally, the amount of detached particles increases with the rainfall intensity.

Surface water may concentrate in depressions or low points within fields, producing shallow drainage lines. These so-called rills are normally less than 30 cm deep and may lead to soil erosion when flushed with surface water runoff. Rill erosion is common in agricultural, often overgrazed land, but also in freshly cultivated soils, where the soil structure has been loosened (Jenkins & Alt 2005). Rills can usually be removed with farm machinery and erosion caused by rills can be reduced by mechanical methods (see Chapter2), such as filter strips, ripped mulch lines and contour drains (Jenkins & Alt 2005).
Channels deeper than 30 cm are called gullies. They occur when rills converge in a concentrated flow or surface runoff. The steeper the soil surface, the higher the velocity of the surface flow and thus, the energy of the erosive forces (Zeedyk & Jansens 2006). This may sometimes lead to deep cuts of tens of metres in depth and width (Pourghasemi et al. 2017). In the gully surface, runoff is concentrated, leading to higher flow velocities. Surface protection is constantly reduced and any disturbance can lead to a migrating headcut, but also lateral widening may occur (USDA 2005).

Gullies can decrease soil productivity dramatically by incising agricultural lands, which consequently leads to restrictions in land use, roads and structures (Pourghasemi et al. 2017). Poesen (2018) state that gullies transfer runoff and sediments from uplands to valley bottoms, increasing the connectivity in the landscape. Hence, many cases of sediment and chemical damage to watercourses and properties by runoff from agricultural land result from gullying. Both rill and gully erosion can contribute significantly to catchment sediment yield and to offsite effects such as flooding and reservoir sedimentations (Vannoppen et al. 2015).
Castillo & Gómez (2016) conducted a meta-analysis of the most relevant studies from the last century regarding gully erosion. Their meta-analysis shows that gully erosion has been described in a large number of countries, led by Spain, the US, Australia, China, Ethiopia and South Africa. Furthermore, their study illustrates that gully erosion exists in all climates (excluding polar climates) and especially in grazing and crop lands, pointing to the direct link between agricultural activities and gully erosion initiation.

Raindrop impact, as well as shallow surface flow (overland flow) can lead to the removal of soil in thin layers, called sheet erosion. These fine soil particles contain a vast amount of nutrients and organic matter and therefore play a significant role with respect to soil quality (Jenkins & Alt 2005). However, with overland flow soil loss occurs gradually and often goes unnoticed, leading to large soil losses. Soils most vulnerable to overland flow erosion are overgrazed and cultivated soils with reduced amounts of vegetation protecting the soil. Early signs of overland flow erosion are bare areas, water puddling as soon as rain falls, visible grass and tree roots, and exposed subsoil or stony soils (Jenkins & Alt 2005). Furthermore, ponding, sheet and rill overland flow may decrease soil infiltration rates, therefore decreasing the availability of water for plant growth (Fernández-Raga et al. 2017).

Wind erosion is a common erosion process above all in arid and semi-arid regions, where soil moisture content is at wilting point or below (Jenkins & Alt 2005). There are three environmental conditions that may set off this wind induced movement of the soils:

1. the wind is strong enough to mobilise the soil particles,
2. the soil texture, as well as organic matter and moisture content make the soil susceptible to wind erosion and
3. there is mostly no vegetation, stones or snow on the soil (Borrelli et al. 2014).

Although wind erosion has always occurred naturally, today the geomorphic effects of wind are locally increased by anthropogenic pressures; e.g. overgrazed rangeland pastures or leaving cultivated areas fallow for longer periods (Borrelli et al. 2014).
Early signs of wind erosion include dust clouds, soil accumulation along fences, and a withered appearance of the soil (USDA 2012).

As this chapter showed, there are many forms in which soil erosion may appear. Nevertheless, soil is principally degraded by the impact of water through erosive forces caused by either rainsplash or runoff. Wind erosion is almost exclusively found in arid and semi-arid regions and only under certain conditions. However, when these conditions occur, also wind erosion may cause severe soil degradation.

Measuring Erosion

The average annual rate of erosion on a field can be predicted with the use of the Universal Soil Loss Equation (USLE). This equation integrates the local rainfall pattern, soil type, topography, crop system and management practices. Nevertheless, the USLE equation has two main limitations. Firstly, the USLE equation is an estimate based on different variable factors. Therefore, the resulting soil loss must be viewed as a long-term average. Secondly, the USLE equation only accounts for soil losses due to sheet or rill erosion on a single slope. Soil losses from gully erosion, wind erosion or tillage are not included (Stone & Hilborn 2012). The Soil Erosion Calculator, which is available at the open access e-learning website www.ruvival.de, is a tool that integrates the USLE equation to directly calculate an estimate of annual soil erosion losses on a specific field. The calculator can be found here.

There is a computerised version of the USLE equation, named Revised Universal Soil Loss Equation (RUSLE). RUSLE is an improved formula that integrates more complex combinations of tillage and cropping practices. RUSLE also includes multiple slope varieties. A further upgraded version is RUSLE2, which can do event-based erosion prediction. RUSLE2 requires expansive input information, which may not be available in all legal systems (Stone & Hilborn 2012).

The most advanced soil erosion simulation system is the Water Erosion Prediction Project (WEPP). It is a physically-based soil erosion calculator, which integrates hydrology, plant science, hydraulics and erosion mechanisms to predict erosion at the hillslope and watershed scale. It is capable of modelling and assessing a variety of land uses, climate and hydrologic conditions. It works offline on personal computers running the Windows operating system (USDA 2016).

Soil Conservation Principles

The aim of soil conservation is to reduce the erosion extent in a way that the maximum amount of sustainable agriculture, grazing or recreational activities can be obtained without damaging the environment. The strategies used for soil conservation must be based on: soil cover to protect it from raindrop impact; increasing infiltration rates to reduce runoff; improving the aggregate stability of the soil; increasing the surface roughness to reduce the velocity of runoff and wind (Morgan 2005).
Erosion is a natural process which cannot be completely prevented. However, it can be reduced. The measures used to prevent soil from eroding can be subdivided into three principles: agronomic measures, soil management and mechanical methods. Depending on the local situation and the cause of erosion a different measure (or a combination of measures) may be favourable.

Agronomic measures most commonly refer to preventing soil from eroding by using a vegetation cover. A soils surface cover is crucial with regard to soil and water conservation and is commonly used to prevent soil and water losses, especially on sloped land (Duan et al. 2017). Land cover can include litter and living vegetation, and it prevents soil erosion in several ways (Vannoppen et al. 2015):

1. It protects the soil surface against raindrop impact and runoff erosion,
2. It decreaces runoff volumes and velocities by enhancing the soils infiltration capacity and its surface roughness, and
3. It reduces sediment transport by capturing sediments.

Over time, planting vegetation will also improve the soil structure and texture (Zeedyk & Jansens 2006). Most attention in scientific literature has been given to above ground mass, as Poesen (2018) points out. Therefore, most models predicting sheet and rill erosion are focussed on plant canopy characteristics. Nevertheless, below ground mass (especially plant roots) play a significant role when incisive erosion processes, such as rill and gully erosion, become dominant (Poesen 2018).

Besides land cover itself, several other land use and management factors affect soil loss, including the type of crop and tillage practices (Panagos, Borrelli et al. 2015). Extensive tillage activities and herbicide treatments keep soils bare and prone to erosion (Keesstra et al. 2016) and should therefore be avoided. Depending on the climatic conditions, tillage may have some beneficial effects with respect to crop yield. Vannoppen et al. (2015) conducted a meta-analysis of 47 European studies that compare crop yields under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) techniques. Their study showed that especially under drier climatic conditions NT did perform worse. RT lead to a reduction in crop yields for maize and winter cereals only. They conclude that conservation tillage (RT techniques, together with crop residue management and crop rotation) may be a viable option for European agriculture from the viewpoint of agricultural productivity. Nevertheless, there is a great amount of literature pointing to the increase of soil erosion rates and the decrease of crop yields due to tillage practices (Heckrath et al. 2005; Lindstrom 2002; Muñoz-Romero et al. 2010).

Ochoa et al. (2016) conducted research on the change of natural cover and discovered that pasture or crops can evoke a rapid decline in organic matter content of soil, leading to depletion and desertification risk. Generally, a deep, medium-textured, moderately permeable soil that has subsoil characteristics favourable for plant growth will be more resistant to soil erosion than soils with shallow root zones or high percentages of shale at the surface (Renard et al. 1997). Plant roots further modify mechanical and hydrological soil characteristics, including the soil aggregate stability by root exudates, soil cohesion, infiltration rate, and the soil moisture and organic matter content. Their effectiveness in reducing concentrated flow erosion is dependent on several root and soil properties, such as root density, root architecture, soil texture, soil moisture (Vannoppen et al. 2015). Consequently, interference with nature such as deforestation should generally be avoided to keep the soil cover in good condition (ed. IPBES 2018; Ochoa et al. 2016).

Mechanical methods are typically based on engineering structures and depend on changing the surface topography to control/reduce the flow of water and air (Morgan 2005). These methods may include the installation of wind breaks, terraces, one-rock dams, log mats, felled trees, brush dams, etc. (Zeedyk & Jansens 2006). Mechanical methods are generally effective for controlling the transport phase of soil erosion, but have only little effect with respect to soil detachment, and are therefore largely ineffective on their own (Morgan 2005).

Finally, it is worth mentioning that agronomic measures in combination with accurate soil management can influence both detachment and transport phases of erosion. Furthermore, preference should always be given to agronomic measures, since these measures are typically inexpensive and directly affect the raindrop impact, further increasing infiltration rates, reducing runoff volumes and decreasing water and wind velocities (Morgan 2005). Lastly, they are usually combinable with existing farming systems and have positive effects on the biodiversity of the ecosystem.

Soil Erosion Control Measures – State of the Art

A meta-analysis with published data from more than 400 sites worldwide was conducted by García-Ruiz et al. (2015), illustrating that globally there is an extraordinarily high variability of soil erosion rates with almost any rate possible under any climate condition. Nevertheless, detailed analysis revealed a positive relationship of soil erosion rates with slope and annual precipitation. Furthermore, a significant effect of land use was detected, with agricultural lands yielding the highest erosion rates, whereas forests and shrublands were yielding the lowest.

A study conducted by Keesstra et al. (2016) investigates the impact of different management strategies on soil properties from agricultural land (fruit orchards) in Vall d'Albaida, Spain. Their findings illustrate that vegetation cover, soil moisture and organic matter were significantly higher in covered plots than in tilled and herbicide treated plots. Especially the use of herbicides (leading to bare soils the whole year round) had a significant effect on soil erosion rates: herbicide treatment caused 1.8 and 45.5 times more erosion than tilled and covered soils, respectively. Moreover, the highest runoff sediment concentrations were found on tilled plots, showing that extensive tillage as well as the use of herbicides should be avoided. The authors further explain that tillage was the only management strategy used by farmers in Vall d'Albaida until the 1990's, when the use of herbicides was introduced, which lead to an increase of runoff and soil losses. Nevertheless, some pioneering farmers used alternative management measures, such as chipping after pruning and spreading the chips on the soil's surface instead of burning them. This led to soil recovery, increasing the soil organic matter and reducing soil bulk density.

Ochoa et al. (2016) conducted a study in the semi-arid Catamayo basin in the Ecuadorian Andes. They found, likewise, that the land cover (often referred to as C-factor) is an important factor to estimate the risk of soil erosion, stating that in protected areas with evergreen vegetation soil erosion risk was very low, even with steep slopes and high annual rainfall amounts. On the other hand, where ground cover was sparse, soil erodibility is the most important factor, especially during the dry season in agricultural areas. They conclude that for semi-arid, mountainous regions, during rainy seasons soil erosion vulnerability is highly influenced by the erosivity factor, followed by the land cover and to a lesser degree topographic and soil erodibility factors. However, during the dry season, soil erodibility and topographic factors become more important, in particular when poor vegetation is present. When looking at the soil cover factor, many results found in literature highlight the positive effects of mulching (Fernández-Raga et al. 2017; Grismer & Hogan 2005; Smets, Poesen & Knapen 2008; Zeedyk & Jansens 2006). Mulching is a common practice, which can act as a forest soil litter cover, protecting the soil against erosion and improving the soil physical properties. It is a very effective practice to control soil erosion, especially by water; however, its effectiveness is variable depending on many other factors, such as slope gradient, soil type, rainfall erosivity, and rate of mulch application (Smets, Poesen & Knapen 2008). Smets, Poesen & Knapen (2008) discovered in an analysis of 41 studies that the plot length is important in determining the effectiveness of a mulch cover in reducing soil erosion by water. In particular, the analysis showed that on short plots, a mulch cover is significantly less effective in reducing relative soil loss by water erosion compared to longer plots.

A state of the art study by Vannoppen et al. (2015) examined the effect of a root variable on different kinds of soil erosion by water. They found that above ground biomass (vegetation cover) was more effective in reducing splash erosion, whereas below ground biomass (plant root system) was more effective in reducing (inter-)rill erosion. Consequently, they suggest a combination of a well-established vegetation cover together with a dense root system in the topsoil as an efficient soil management strategy against water erosion. To further improve this strategy, Berendse et al. (2015) recommend using a variety of plant species for the soil cover. In a three-year long field experiment they investigated the effect of 1, 2, 4 and 8 plant species on soil loss through erosion on a simulated dike. They found that erosion resistance was reduced with loss of plant species diversity. Their analysis revealed that the main mechanism explaining the strong effects of plant species diversity on soil erosion is the so-called insurance effect: 'the capacity of diverse communities to supply species to take over functions of species that went extinct as a consequence of fluctuating environmental conditions' (Berendse et al. 2015, p. 881). This leads to the assumption that especially in changing climates, a high variety of soil cover species is beneficial for protecting and restoring soils. A further study by Fattet et al. (2011) examined the effect of tree planting, a common practice, on soil conservation. They found that planting trees is not always the best solution, especially in steep terrains, since the understory vegetation is often removed mechanically or cannot grow in shady conditions, resulting in increased runoff and interrill erosion. Moreover, root biomass density and root depth is usually lower than in natural forests at an equivalent age, augmenting the risk of shallow landslides, particularly in regions with very high rainfall events (Monsoons etc.).

There are many studies pointing to the importance of the infiltration rate of a soil for its capability to resist erosion (Duan et al. 2017; Grismer & Hogan 2005; Keesstra et al. 2016; Smets, Poesen & Knapen 2008; Zeedyk & Jansens 2006). Duan et al. (2017) conducted a study in southern China investigating the effect of rainfall patterns and land cover on runoff generation processes. They found that the total runoff and surface flow values were highest for bare land under all four investigated rainfall patterns and lowest for the covered plots. The soil cover leads to a decrease in total runoff by increasing the soil water storage capacity and infiltration rates. Mixing topsoil and vegetation litter (such as roots) increased the hydraulic conductivity and permeability of the topsoil, providing favourable conditions for subsurface flow generation.
In general, if a soil has characteristics that prohibit infiltration of water (e.g. crusting, slacking, lack of macro pores) the runoff coefficient will be higher, leading to more erosion. However, if the soil has a rough or covered surface, the runoff will be delayed by ponding water, allowing water to infiltrate and reducing soil erosion on such sites (Keesstra et al. 2016).

In case that it is not possible to improve the soil structure by vegetation cover, Zeedyk & Jansens (2006) suggest to direct water to sites where infiltration occurs or is enhanced (in comparison to depleted soil). Slowed down water can soak in more easily and cling to soil particles, additionally enlivening microorganisms which help transport water from pores in the soil to plant roots. Also, if moisture is retained long enough, dormant seeds in the soil may germinate. In particular for dry regions with scarce rainfall events, Zeedyk & Jansens (2006) recommend the use of the following water harvesting techniques:

1. Structures that retain or divert stormwater runoff, such as rolling dips, diversion drains, swales and berms, and micro-catchments;
2. Structures that slow the flow of water, increasing the infiltration time, such as one-rock dams, rock lines on contour, straw wattles, and strawbale dams;
3. Mulching the soil with organic mulch, which protects the soil against wind erosion and evaporation and adds organic matter while decomposing.

Grismer & Hogan (2005) compared different soil treatment methods for granitic and volcanic soils in the Lake Tahoe Basin (USA), a semi-arid, high-altitude environment of relatively shallow soils, minimal summer rains and long winters. These treatments involved pine-needle mulching, use of compost and planting a grass/vegetation cover. Their results show that the average sediment concentrations declined for the granitic soils by approximately 50 % and sediment yields fell by over 30 % due to the improved soil tilth, water-holding capacity, nutrient cycling and increased infiltration rates. On the other hand, since volcanic soils contain more fine-sized particles and have relatively high runoff sediment concentrations (in comparison to granitic soils), the grass treatments only reduced rainfall splash erosion, while offering little additional infiltration capacity. They conclude that especially for bare volcanic soils, a more complete restoration is necessary to increase the soils infiltration capacity.

Apart from soil management strategies, a crucial element in conserving our soils is the education of land owners, as some literature point out (Arnalds 2005; FAO 2014; Ochoa et al. 2016; Panagos, Ballabio et al. 2015). Ochoa et al. (2016) state that especially in developing countries, where there is a high demand for timber, farmers tend to exploit their lands using slash-and-burn-agriculture for quick profits instead of long-term use of their forests. Therefore, the authors propose more environmental education and land conservation policies. Arnalds (2005) investigated the effects of different soil conservation programmes in Iceland. His study shows that top-down approaches often lacked in incentives for land-user participation. On the other hand, he states that instead of implementing single-issue soil conservation methods, more holistic and integrated approaches to land husbandry were helpful. Concluding, FAO (2014)recommends the implementation of strong regulations and associated governmental investments, as our soils crucially contribute to the extinction of hunger and poverty.

Conclusion

Soil erosion is found all over the world and its dependency on climate conditions, present soil characteristics and topographic circumstances makes the rate at which erosion occurs highly variable. Consequently, there is no single soil management strategy generally applicable.
Nevertheless, there are some conclusions to be drawn from the literature:

1. Agronomic measures, especially covering the soil with vegetation, are highly beneficial as they increase the soil moisture and organic matter content, further improving infiltration rates and in the long term leading to dense root systems. It is furthermore recommended to use a variety of plant species to enhance the so-called *insurance effect*. The benefits of a well-established vegetation cover were approved for almost all regions and conditions;
2. A combination of agronomic measures and soil management will lead to higher soil resistances, since agronomic measures are generally more effective against splash erosion, whereas a high amount of underground biomass makes the soil more resistant against rill erosion,
3. Mechanical methods should generally be used as additional erosion control strategies to support agronomic measures and soil management, but never as stand-alone soil conservation measures, as they are typically expensive to construct and maintain, and there is no noticeable effect against soil particle detachment.

A specific soil conservation measure to be highlighted is the use of organic mulch. It functions as a mixture between agronomic measures and soil management, directly protecting the soil against water erosion and improving the soil physical properties. However, it should be noted that the effectiveness of a mulch cover is dependent on the plot size, showing better effects with increasing plot sizes.
Lastly, it should be mentioned that the conservation of our soils is not only a technical and scientific matter, but also a political one. Governments and municipalities should stand the duty to educate local farmers on how to conserve their soils and provide them with financial incentives to prevent exploitation of arable lands for quick revenues. Moreover, strong regulations need to be implemented to further ensure a sustainable use of our soils.

References

Arnalds, A 2005, ‘Approaches to landcare: A century of soil conservation in Iceland’, *Land Degradation & Development*, vol. 16, no. 2, pp. 113–25.

Berendse, F, van Ruijven, J, Jongejans, E & Keesstra, S 2015, ‘Loss of Plant Species Diversity Reduces Soil Erosion Resistance’, *1432-9840*, vol. 18, no. 5, pp. 881–8, viewed 11 November 2017, <https://link.springer.com/article/10.1007/s10021-015-9869-6>.

Borrelli, P, Ballabio, C, Panagos, P & Montanarella, L 2014, ‘Wind erosion susceptibility of European soils’, *Geoderma*, 232-234, pp. 471–8.

Castillo, C & Gómez, JA 2016, ‘A century of gully erosion research: Urgency, complexity and study approaches’, *Earth-Science Reviews*, vol. 160, pp. 300–19.

Duan, J, Yang, J, Tang, C, Chen, L, Liu, Y & Wang, L 2017, ‘Effects of rainfall patterns and land cover on the subsurface flow generation of sloping Ferralsols in southern China’, *PLOS ONE*, vol. 12, no. 8.

Fattet, M, Fu, Y, Ghestem, M, Ma, W, Foulonneau, M, Nespoulous, J, Le Bissonnais, Y & Stokes, A 2011, ‘Effects of vegetation type on soil resistance to erosion: Relationship between aggregate stability and shear strength’, *0341-8162*, vol. 87, no. 1, pp. 60–9, viewed 6 December 2017, <http://www.sciencedirect.com/science/article/pii/S0341816211000907>.

Fernández-Raga, M, Palencia, C, Keesstra, S, Jordán, A, Fraile, R, Angulo-Martínez, M & Cerdà, A 2017, ‘Splash erosion: A review with unanswered questions’, *Earth-Science Reviews*, vol. 171, pp. 463–77.

Food and Agriculture Organization of the United Nations 2014, *Global plans of action endorsed to halt the escalating degradation of soils*, News Article, Rome, viewed 23 October 2017, <http://www.fao.org/news/story/en/item/239341/icode/>.

García-Ruiz, JM, Beguería, S, Nadal-Romero, E, González-Hidalgo, JC, Lana-Renault, N & Sanjuán, Y 2015, ‘A meta-analysis of soil erosion rates across the world’, *Geomorphology*, vol. 239, pp. 160–73.

García-Ruiz, JM, Nadal-Romero, E, Lana-Renault, N & Beguería, S 2013, ‘Erosion in Mediterranean landscapes: Changes and future challenges’, *Geomorphology*, vol. 198, pp. 20–36.

Grismer, ME & Hogan, MP 2005, ‘Simulated rainfall evaluation of revegetation/mulch erosion control in the Lake Tahoe basin—3: Soil treatment effects’, *Land Degradation & Development*, vol. 16, no. 5, pp. 489–501.

Heckrath, G, Djurhuus, J, Quine, TA, van Oost, K, Govers, G & Zhang, Y 2005, ‘Tillage Erosion and Its Effect on Soil Properties and Crop Yield in Denmark’, *Journal of Environmental Quality*, vol. 34, no. 1, pp. 312–24.

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (ed.) 2018, *Summary for policymakers of the thematic assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, Bonn, Germany.

Jenkins, A & Alt, S 2005, *Fact sheet 1: Types of erosion*, Soil erosion solutions, Northern Rivers Catchment Management Authority & NSW Department of Industry, New South Wales, viewed 20 December 2017, <https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/255153/fact-sheet-1-types-of-erosion.pdf>.

Keesstra, S, Pereira, P, Novara, A, Brevik, EC, Azorin-Molina, C, Parras-Alcántara, L, Jordán, A & Cerdà, A 2016, ‘Effects of soil management techniques on soil water erosion in apricot orchards’, *Science of the Total Environment*, 551-552, pp. 357–66.

Larson, D, Delgado, L & Carnes, J 2014, *Design Report*, Tsegi wash capstone project, Northern Arizona University, Arizona, viewed 2 March 2018, <https://www.cefns.nau.edu/capstone/projects/CENE/2014/TsegiWash/files/Final%20Design%20Report.pdf>.

Lindstrom, M 2002, 'Tillage Erosion: Description and Process', in R Lal (ed.), *Encyclopedia of soil science*, Marcel Dekker, New York, pp. 1324–6.

Martín-Fernández, L & Martínez-Núñez, M 2011, 'An empirical approach to estimate soil erosion risk in Spain', *The Science of the total environment*, vol. 409, no. 17, pp. 3114–23.

Morgan, RPC 2005, *Soil erosion and conservation*, 3rd edn, Blackwell Pub, Malden.

Morgan, RPC & Rickson, RJ (eds) 1994, *Slope stabilization and erosion control: A bioengineering approach*, 1st edn, E & FN Spon, London.

Muñoz-Romero, V, Benítez-Vega, J, López-Bellido, L & López-Bellido, RJ 2010, 'Monitoring wheat root development in a rainfed vertisol: Tillage effect', *European Journal of Agronomy*, vol. 33, no. 3, pp. 182–7.

Ochoa, PA, Fries, A, Mejía, D, Burneo, JI, Ruíz-Sinoga, JD & Cerdà, A 2016, 'Effects of climate, land cover and topography on soil erosion risk in a semiarid basin of the Andes', *0341-8162*, vol. 140, Supplement C, pp. 31–42, viewed 11 November 2017.

Panagos, P, Ballabio, C, Borrelli, P, Meusburger, K, Klik, A, Rousseva, S, Tadić, MP, Michaelides, S, Hrabalíková, M, Olsen, P, Aalto, J, Lakatos, M, Rymszewicz, A, Dumitrescu, A, Beguería, S & Alewell, C 2015, 'Rainfall erosivity in Europe', *The Science of the total environment*, vol. 511, no. 511, pp. 801–14.

Panagos, P, Borrelli, P, Meusburger, K, Alewell, C, Lugato, E & Montanarella, L 2015, 'Estimating the soil erosion cover-management factor at the European scale', *Land Use Policy*, vol. 48, pp. 38–50, viewed 11 November 2017.

Panagos, P, Meusburger, K, Ballabio, C, Borrelli, P & Alewell, C 2014, 'Soil erodibility in Europe: a high-resolution dataset based on LUCAS', *The Science of the total environment*, 479-480, Supplement C, pp. 189–200, viewed 11 November 2017.

Poesen, J 2018, 'Soil erosion in the Anthropocene: Research needs', *Earth Surface Processes and Landforms*, vol. 43, no. 1, pp. 64–84.

Pourghasemi, HR, Yousefi, S, Kornejady, A & Cerdà, A 2017, 'Performance assessment of individual and ensemble data-mining techniques for gully erosion modeling', *The Science of the total environment*, vol. 609, pp. 764–75.

Reinisch, I 2015, *How water drops impact soil surfaces*, Video, Department of Soil Science Faculty of Organic Agricultural Sciences University of Kassel, viewed 28 November 2017, <https://vimeo.com/130951674>.

Renard, KG, Foster, GR, Weesies, GA, McCool, DK & Yoder, DC 1997, *Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE)*, Agriculture handbook, vol. 703, United States Department of Agriculture, Washington.

Rodrigo Comino, J, Brings, C, Lassu, T, Iserloh, T, Senciales, JM, Martínez Murillo, JF, Ruiz Sinoga, JD, Seeger, M & Ries, JB 2015, 'Rainfall and human activity impacts on soil losses and rill erosion in vineyards (Ruwer Valley, Germany)', *Solid Earth*, vol. 6, no. 3, pp. 823–37.

Smets, T, Poesen, J & Knapen, A 2008, 'Spatial scale effects on the effectiveness of organic mulches in reducing soil erosion by water', *Earth-Science Reviews*, vol. 89, 1-2, pp. 1–12.

Stone, RP & Hilborn, D 2012, *Universal Soil Loss Equation (USLE)*, Fact Sheets, October 2015, Ministry of Agriculture, Food, and Rural Affairs, Ontario, viewed 24 March 2018, <http://www.omafra.gov.on.ca/english/engineer/facts/12-051.htm#t5>.

United States Department of Agriculture 2005, *Concentrated Flow Erosion*, Soil, United States Department of Agriculture, viewed 6 December 2017,

<https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1187269.pdf>.

——2012, *Sheet, Rill and Wind Erosion*, Soil, United States Department of Agriculture, viewed 20 December 2017, <https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1187270.pdf>.

——2016, *National Soil Erosion Research: West Lafayette, IN*, 10 March, United States Department of Agriculture, viewed 14 April 2018, <https://www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosion-research/docs/wepp/research/>.

Vannoppen, W, Vanmaercke, M, Baets, S de & Poesen, J 2015, 'A review of the mechanical effects of plant roots on concentrated flow erosion rates', *Earth-Science Reviews*, vol. 150, pp. 666–78.

Vrieling, A, Hoedjes, JCB & van der Velde, M 2014, 'Towards large-scale monitoring of soil erosion in Africa: Accounting for the dynamics of rainfall erosivity', *Global and Planetary Change*, vol. 115, pp. 33–43.

Zeedyk, B & Jansens, J-W 2006, *An Introduction to Erosion Control*, 2nd edn, Earth Works Institute, The Quivira Coalition & Zeedyk Ecological Consulting, Santa Fe, NM, viewed 23 October 2017, <http://allaboutwatersheds.org/library/general-library-holdings/ErosionControlFieldGuide_000.pdf>.

Zhao, G, Mu, X, Wen, Z, Wang, F & Gao, P 2013, 'Soil erosion, conservation, and eco-environment changes in the loess plateau of china', *Land Degradation & Development*, vol. 11, no. 1, 499–510, viewed 11 November 2017.