

Influence of Vegetation on the Development of Erosion Between Furrows in a Semi-arid Environment

ABSTRACT

Soil is a vital component of the planet, fundamental to many aspects of the agrarian sciences, in the last years this resource has been abruptly degraded, due to urban development and anthropogenic actions, leading to significant yield losses on agricultural crops, representing a threat to food security and limiting the production of renewable biological resources. Erosion is seen as one of the most destructive soil processes, it is estimated that man has already degraded 53 billion hectares in the world, by improper use of the soil, leading to the deterioration of its physical, chemical and biological properties. In tropical and subtropical zones the annual soil loss varies between 0.28 and 113 t ha⁻¹, depending on annual precipitation, landscape and land use. Arid and semi-arid regions are considered fragile environments, where plant cover is scarce and where soil erosion processes occur rapidly and severely after rainfall events. However, even under these conditions, the importance of native vegetation is very relevant in the regulation of surface hydrological processes.

Keywords: erosion between furrows, vegetal cover, semiarid environment, food safety, sustainable production, erosion by rain.

1. INTRODUCTION

Soil is a vital component of the planet, fundamental to many aspects of the agrarian sciences [1], in the last few years this resource has been abruptly degraded, due to urban development and anthropogenic actions, leading to significant yield losses on agricultural crops [2,3,4], representing a threat to food security and limiting the production of renewable biological resources [3,4].

The environmental problems are presenting great dimensions, causing, therefore, changes around the globe, the problems related to soil degradation are among the most worrying [5]. Soil erosion is a major environmental problem responsible for large soil losses, imbalances in the environment, as well as a decrease in productivity of cultivated lands [6].

Erosion is seen as one of the most destructive soil processes, it is estimated that man has already degraded 53 billion hectares of the terrestrial globe, by inappropriate use of the soil, leading to deterioration of its physical, chemical and biological properties [7,8]. In tropical and subtropical zones the annual soil loss varies between 0.28 and 113 t ha⁻¹, depending on the annual precipitation, landscape and land use [9].

Arid and semi-arid regions are considered fragile environments, where vegetable cover is scarce and where soil erosion processes occur rapidly and severely after rainfall events. However, even under these conditions, the importance of native vegetation is very relevant in the regulation of surface hydrological processes. According to [10], vegetation removal is the main cause of soil degradation in semi-arid areas. Changes in soil properties induced by vegetation removal modify the runoff and response to soil erosion in a semi-arid area.

In the last decades, soil erosion has been increasingly recognized as a serious environmental problem in semi-arid regions. Recent studies conducted in southern Italy (semi-arid Mediterranean) have soil erosion rates ranging from 10-85 t ha year⁻¹, in areas covered by vegetation [11] and from 100-150 t ha year⁻¹, in cultivated lands [12]. These high erosion rates reflect the impact caused by human activity.

The rainfall regime in semi-arid areas is characterized by events of extremely short duration and with very high intensity, besides an irregular spatio-temporal distribution, followed by long periods of drought, making these areas environments particularly prone to erosion [13]. Human activities further increase the risk of erosion, between them, the creation of bare surfaces on cultivated land after plowing operations and subsequent abandonment of land [11].

Soils in semi-arid regions are characterized by low levels of organic matter and high levels of expansive clay [14], properties that may decrease the stability of the soil structure [15]. Making them very susceptible to water erosion [16], mainly due to the scarce vegetation cover and the low resistance to erosion forces. The magnitude of water erosion also depends on its texture, water content, evaporation, percolation and leaching. The soil characteristics of these regions are not favorable for soil resistance to water erosion [17].

When these soils are exposed to the impact of raindrops, a structural seal develops on the surface of the soil, called surface sealing [15,18], a thin layer (a few millimeters) characterized by having a higher density, and lower hydraulic conductivity than the underlying soil [19,20].

According to [21], the formation of surface sealing is the result of two complementary mechanisms: (i) the physical disintegration of the aggregates at the soil surface caused mainly by the kinetic energy of the impact of the raindrops, and (ii) the dispersion of the clay particles, which clog the pores immediately below the surface of the soil, forming the surface sealing [18].

The erosive process involves the processes of: (i) the disintegration of the soil particles from its surface, (ii) the transportation of the resulting sediments, mainly by the action of surface runoff, and (iii) sediment deposition [22]. Soil erosion reduces water availability on the field scale by affecting its quality and storage. The complete suppression of vegetation can also lead to irreversible soil degradation in semi-arid areas [10].

According to [23] the loss of water and soil by surface runoff on eroded slopes is maximized by different mechanisms: reduction of roughness, the effective evacuation of water flows from the inclination by the networks of the grooves, which increase the connectivity of the runoff on the slopes and open efficient ways to conduct water out of the system, and the reduction of water infiltration by formation of surface crusts, which are thin layers of organic and mineral particles on the soil surface, affect soil disaggregation [24], altering, infiltration of water in the soil and surface runoff [25].

There are a number of factors that control erosion, among them we can mention: the angle of land slope, the nature and type of vegetation cover, the erodibility and the type of soil management [26]. The vegetation-soil system has mechanisms that regulate soil formation, vegetation development and erosion and sedimentation processes [27].

In semiarid environments it is conventional to use agriculture of dry land, where the rural producer removes all the vegetation from the river banks for the planting of agricultural species [28]. To occur sustainable production farmers must have a selection of integrated management options [29], which will provide sufficient benefits with reasonable costs and, at the same time, reduce the degradation of drylands and maintain sustainable incomes, such as the application of conservation strategies [30,31].

The implemented strategies should include agronomic measures of soil surface manipulation, such as coverage dead and changes to prevent and control land degradation and improve field-scale productivity. Despite government efforts to reverse soil erosion processes at the river basin scale, the pluviometric regime of semi-arid regions is very problematic, causing degradation and inefficiency in land use [32], and even in years of sufficient annual precipitation yields remain low [33].

For [34], in a semi-arid environment, the preservation and / or restoration of vegetation can effectively reduce surface runoff and sediment transport. Native forests are more effective in soil erosion control [35]. Some researchers, but not all of them, state that a mixed pattern of trees and shrubs would be ideal for inhibiting soil erosion.

2. EROSION BETWEEN FURROWS

Soil erosion comprises two main components, erosion in between furrows and the furrow erosion [36]. Erosion in between furrows happens when there are no incisions in the surface of the ground realized by the surface runoff, the most important factor at that moment is the breakdown of the soil by the impact of raindrops on its surface, and the existence of a blade of runoff that seems to carry more than disaggregate the soil [37]. The surface runoff that occurs in erosion in between furrows is, frequently, called shallow laminar flow [38].

Several are the negative effects on erosion between furrows, highlighting the reduction of soil fertility, off-site effects triggered by sediment transport, nutrients, and pollutants, causing great efforts to mitigate damages, with high costs [39,40], affecting nutrient cycling and the functioning of the ecosystem [41,42].

Erosion between furrows can also lead to the emergence of poor, hard soils, with low water storage capacity [43]. In the Revised Universal Soil Loss Equation (RUSLE), which is used to predict soil loss rates, the proportion of erosion between furrows is a very important parameter [44], the same importance is equivalent to other models based on recent processes, for example, LISEM [45], WEPP [46], EUROSEM [26], and PSEM-2D. However, it is difficult to directly measure erosion rates in between furrows, because of the difficulty of observing the furrow erosion processes associated with costs and the intensive work in the field [47].

The parameter of erodibility between furrows, which expresses soil resistance to erosion between furrows is used along with other parameters, including rainfall erosivity, slope characteristics, hydraulic factors, and the vegetation cover, which is one of the most important parameters for the study of erosion between furrows [48], in addition to soil type and land use [49].

The vegetation cover has an important effect on soil erosion, the vegetable residues on the surface act by intercepting the raindrops and dissipating their energy, avoiding the disintegration of the particles and the formation of surface sealing. In addition, occurs the reduction of the velocity of the surface flow and, consequently, a reduction in their disaggregation capacity and transport of soil particles [50]. [51] found an exponential reduction of erosion between furrows with the increase in soil cover attributed to residues of maize and wheat.

To [52] the erosion in between furrows, the reduction of the flow velocity caused by the presence of vegetables residues on the surface occurs, generally because of the increase in hydraulic roughness of surface flow, resulting in increased flow height [51,53]. The relationship between the rates of disaggregation and the presence of plant residues in erosion between furrows is expressed, according to [53], below:

$$D_i = K_i I^2 S_f C_i \quad (1)$$

where D_i is the rate of soil disaggregation ($\text{kg m}^{-2} \text{s}^{-1}$); I is the intensity of the rain (m s^{-1}); S_f is the slope factor; C_i is the coefficient of soil cover. This coefficient C_i combines several subfactors, according to the expression:

$$C_i = C_{il} C_{ill} C_{iill} \quad (2)$$

where C_{il} is the factor that expresses the effect of cover of canopy; C_{ill} is the factor that expresses the effect of the cover by residues in direct contact with the surface of the soil; C_{iill} is the factor that expresses the effect of the residue incorporated in the soil. The effect of residues in direct contact with the soil surface was evaluated by some authors, that proposed relations capable of quantifying the effect of this roughness said of form, which translates into resistance to run-off and, therefore, reduction of soil disaggregation rates. [53] proposed the following expression:

$$C_{iill} = \xi \exp \{-0.21 [(y_c / y_d) - 1] 1.18\} \quad (3)$$

where C_{iill} is the factor that expresses the effect of the cover by residues in direct contact with the soil surface; ξ is the fraction of surface exposed to the impact of rain; y_c / y_d is the ratio of blade height of flow with coverage (y_c) and without coverage (y_d). [54] developed a simpler expression:

$$C_i II = e^{2.5CS} \quad (4)$$

where C_{iII} is the factor that expresses the effect of the cover by residues in direct contact with the soil surface; e is the basis of the neperian logarithm; CS is the soil cover ($m^{-2} m^{-2}$). [55] obtained an excellent adjustment for the simple model of power to follow:

$$C_i II = abCS$$

where $a = 1.014$; $b = 0.08203$ for a r^2 of 0.992.

3. FACTORS THAT INTERFERE IN THE DISAGGREGATION AND SOIL LOSSES

The disaggregation of Soil in erosion between furrows is defined as the displacement of soil particles from a soil mass at a specific location on the surface, by the kinetic energy of the raindrops, being the surface runoff the main transport agent, which may lead to the formation of furrows and gullies [56,57,58,59,60]. The mechanisms of soil disaggregation by erosion between furrows and erosion in grooves are different and, therefore, they are considered separate processes [61].

Effects of capacity of disaggregation of soil in erosion between furrows have been studied extensively under different environmental conditions, both in the laboratory and in field experiments, using hydraulic parameters such as: the flow regime, liquid discharge, slope, velocity, and sediment concentration [59,62,63,64]. Erosive processes are also controlled by soil erodibility [65].

Soil erodibility is mainly related to soil properties and vegetation characteristics. Soil type, texture and physical-chemical properties of soil: porosity, density, cohesion, clay content, stability of aggregates, organic matter content, soil moisture and infiltration rate, demonstrating a close relationship with the soil disaggregation capacity [26,66,67,68,69].

Soil disaggregation capacity could be stipulated through the mean diameter of the aggregates, content of clay, density of soil and resistance of soil. [70] showed that the soil disaggregation capacity decreased with the increase of soil organic matter, increased moisture content and increased soil density. Any changes in soil properties will surely alter the erodibility of this soil [71,72,73,74,75].

4. IMPORTANCE OF VEGETATION

Vegetation cover has been recognized as a key factor in protection against erosion, increasing the infiltration and surface roughness of the soil, besides reducing the impact of raindrops [76]. The vegetal cover protects the soil, mainly by intercepting the precipitations and reducing the flow velocity of water [77,78]. In addition, the root system increases the stability of soil aggregates and soil water infiltration rates [77,79,80].

However, although the positive influence of the vegetation increasing the rates of infiltration and decreasing soil erosion, little attention has been paid to the ecological effects of soil erosion [81,82]. In this way, several papers indicate a critical role of the knowledge of the erosion-vegetation interactions for the understanding of the processes of degradation in limited water environments, especially in the current context of land use and climate change [83,84,85].

In theory, both the morphological characteristics of plants, such as the diameter of the root, and biomechanical characteristics, the resistance to root traction, have significant effects on soil erosion [48,80].

Diversity of species is one of the main factors for the success of vegetation in controlling soil erosion, the functional diversity of tree communities plays a key role in improving ecosystem services, such as water filtration, climate regulation or erosion control [85,86,87]. As forests are generally considered to be beneficial for erosion control, reforestation is a common measure of soil protection [88,89].

Different forms of soil-vegetation relationship can probably be explained by different types of vegetation that present specific characteristics above the soil (leaves and stems), below ground (roots) and spatial distributions [77,90,91,92,93]. Little is known about the effects of plant diversity on

soil protection [94]. It was hypothesized that a plant cover with a high number of species of plants of different forms of growth, functional groups and root characteristics will be more effective in controlling the processes of erosion between furrows than a cover of vegetation with few species and a lower number of different forms of growth [95].

A recent study conducted by [80] in the Swiss Alps showed a significant positive correlation between soil aggregates stability and plant species richness. These authors assume that with the increase of plant species, increased the richness of the number of root types, resulting in beneficial effects on the stability of soil aggregates.

Positive effects of aerial biomass on erosion control are generally attributed to reductions in the kinetic energy of raindrops and reduced surface runoff velocities [27]. Besides that, plant cover changes intrinsic soil properties, such as erodibility [48], act in the creation of a microclimate and in the supply of organic matter, that affect the activity of microorganisms, and hence the availability of nutrients, resulting in positive feedback on plant productivity.

Both organic matter, as well as microfauna and fungal secretions improved the formation of stable aggregates [27,96], affecting the hydraulic conductivity and, therefore, the capacity of water storage [27] being able to increase the resistance from soil to shear [97,98].

In an attempt to understand the erosive processes with different vegetation cover, [55], researching in Lavras, southeastern Brazil, evaluated the influence of vegetation cover on the control of water and soil losses. [99], studying the use of land in the center of the State of Rio Grande do Sul, show that, with a 16.2% increase in forest area, the gross erosion was reduced by 44%.

Removal of vegetation causes increases of surface runoff, soil erosion, downstream flooding [100,101], and export of sediments, organic matter, nutrients and pollutants which may endanger aquatic habitats and downstream from the flood zone, in addition to associated human infrastructures [102,103].

5. EFFECTS OF ROOTS ABOUT THE ERODIBILITY OF THE SOIL

Erodibility is the result of various mechanical processes, adhesives and bonding forces acting within the soil matrix [65] and should be considered as a "sum of a highly complex response pattern, strongly influenced by the intrinsic and extrinsic characteristics of the soil" [104]. The erosion response may be influenced by any soil property, but will be dominated by shear force, stability of the aggregates and hydraulic function of the soil [104]. Roots can alter soil erodibility through its effect on these soil properties.

Firstly, the roots have a high tensile strength [48,98] allowing up to 100% of the cohesive strength of a root permeating the soil [105], thus increasing the shear strength. The additional tensile force associated with roots is responsible for the transfer of shear stresses through elastic resistance, or friction interface within the soil-root matrix [98,106].

Secondly, the roots prevent sediment transport, retaining disaggregated soil particles [79] and increasing the number of stable aggregates, due to their shear effect [107], the same also happens to fungal hyphae [107,108,109] which act through the release of various agents of binding organic and inorganic [110].

Root exudates, such as mucilages are considered the main mechanism of plant roots that improve the stability of aggregates [109,111]. The mucilage exuded by the roots expand a wet floor covering soil particles, during subsequent drying the contraction of the mucilage occurs, pulling the soil particles tightly in set to form a rhizosheath, thus reorienting the particles to the parallel axis of the root [110,112,113,114].

In addition, root exudates are associated with the release of polyvalent cations, which form strong bonds between organic molecules and clays [110,112,115]. Increasing the amount of ions in the soil solution, significantly increases the stability of aggregates [115]. The decomposition of roots and fungal hyphae also represent a source of organic matter [107,110,112], which contribute to greater

stability to soil aggregates. Thus, the stability of aggregates is enhanced by biological activity (both vegetable as fungal) within the soil.

Root exudates represent 5 to 21% of the carbon (C) fixation of a plant [116] serving as a source of essential energy for microorganisms [107,110]. Fungi and soil bacteria produce polymeric substances that contribute to the cementation of aggregates and, thus, increase its resistance [104,107,111,112,113].

However, the effect of roots on the stability of aggregates is specific of plant specie present in this soil [107,110] due to differences in root morphology [80], the growth rates [117], the chemical composition, the amount of root exudates and the influence of differences of root exudates on microbial activity [107,118]. [107] showed that barley roots (*Hordeum vulgare*) increased the stability of the aggregates, but there is conflicting evidence about the effects of corn roots (*Zea mays*).

Corn root mucilage would have an increase in soil aggregation [111], but, the same, releases chelating agents, such as organic acids (which destroy iron and aluminum bonds with organic matter) decreasing the stability of the aggregates [112]. These contrasting results can be attributed to genotypic variation in the chemistry of root exudates.

Roots can also provide an increase in infiltration rates, since they increase the roughness of the soil [79], while the absorption of water through roots [119] and the creation of continuous pore spaces increase the infiltration capacity, reducing the surface runoff [104,119,120]. [121] found a positive correlation between infiltration rates and root density to the needle grass (*Stipa tenacissima*) and, to a lesser degree, for downy banana (*Plantago albicans*), while obscure results were obtained for albaïda (*Cytisoides anthyllis*) and white absinthe (*Artemisia herba-alba*).

Several authors [122,123,124,125] suggest that live roots form flow pathways, and increase infiltration rates over time, as a result of channels created by the decomposition of these roots. [122] observed that infiltration rates in a sandy soil tripled within 3 years of alfalfa cultivation, [124] observed a significant increase in infiltration rates for the last half of the maize growing season, and after harvest.

A frequently used parameter that sufficiently describes the effectiveness of a species to control erosion rates is the root length density (RLD). RLD is the total root length divided by the volume of soil sample permeated by the root [79], thus providing information on land use by the roots [79,126,127]. Under cereal and grass plants in Belgium, erosion rates declined exponentially with a linear increase in RLD [128]. However, the ability of roots to strengthen a soil is determined not only by root characteristics such as RLD, but also by their distribution in the soil.

In short, [127] reported that the ability of roots to reduce soil erosion was greater than that suggested in previous studies [129,130]. To simulate the effects of roots on soil disaggregation, different root parameters, that is, dry weight, mass density, density of length, diameter, surface area density, and an area of reason, should be taken into account [127]. The effects of erosion reduction as a function of the roots are also affected by the root architecture. In general, pivotal roots reduce erosion rates to a lesser extent, compared to fasciculate roots [127,129,130].

6. CONCLUSION

In view of the foregoing, is perceived that the vegetation cover has an important effect on soil erosion, the vegetable residues on the surface act by intercepting the raindrops and dissipating their energy, avoiding the disaggregation of the particles and the formation of surface sealing. In addition, it occurs to reduce the velocity of the surface runoff and, consequently, reduction in its capacity of disaggregation and transport of soil sediments.

REFERENCES

1. Brevik EC, Cerdà A, Mataix-Solera J, Pereg L, Quinton JN, Six J, Van Oost K. The interdisciplinary nature of soil. Soil. 2015;1(1):117-129.
2. Lal R. Soil degradation by erosion, Land Degrad. Dev. 2001;12(1):519- 539.

3. Pimentel D. Soil erosion: a food and environmental threat. *Envir. Develop. Sustain.* 2006;8(1):119-137.
4. Jankauskas B, Jankauskiene G, Fullen MA. Soil erosion changes in the physical properties of Lithuanian Eutric Albeluvisols under different land use systems. *Acta Agric. Scand. Sect.* 2008;58(1):66-76.
5. Cunha SB, Guerra AJT. Environmental degradation. In: Guerra AJT, Cunha SB. *Geomorphology and the Environment*. 3 th ed. Rio de Janeiro: Bertrand Brazil; 2000.
6. Davison P, Hutchins MG, Anthony SG, Betson M, Johnson C, Lord EI. The relationship between potentially erosive storm energy and daily rainfall quantity in England and Wales. *Sci. of the Tot. Envir.* 2005;344(2):15-25.
7. Brady NC, Weil RR. *Elements of nature and soil properties*. 3 th. Porto Alegre: Bookman; 2013.
8. Ibáñez J. A model-based integrated assessment of land degradation by water erosion in a valuable Spanish rangeland. *Envir. Model. and Soft.* 2014;55(1):201-213.
9. Guo Q, Hao Y, Liu B. Rates of soil erosion in China: A study based on runoff plot data. *Catena.* 2015;124(1):68-76.
10. Castillo VM, Martínez-Mena M, Albaladejo J. Runoff and soil loss response to vegetation removal in a semiarid environment. *Soil Sci. Soc. of Amer. Jour.* 1997;61(4):1116-1121.
11. Porto P, Walling DE. Validating the use of ¹³⁷Cs and ²¹⁰Pbex measurements to estimate rates of soil loss from cultivated land in southern Italy. *Jour. of Envir. Radioac.* 2012;106(1):47-57.
12. Porto P, Walling DE, Callegari G. Using ¹³⁷Cs measurements to establish catchment sediment budgets and explore scale effects. *Hydrol. Proc.* 2011;25(1):886-900.
13. Hötzl H. *Climatic Changes and Water Resources in the Middle East and North Africa.* Environmental Science and Engineering. Berlin: Springer; 2008.
14. Singer A. *The Soils of Israel.* Berlin-New York: Springer-Verlag; 2007.
15. Ben-Hur M. Seal formation effects on soil infiltration and runoff in arid and semiarid regions under rainfall and sprinkler irrigation conditions. In: Zereini F, Hötzl H, editors. *Climatic Changes and Water Resources in the Middle East and North Africa.* Berlin: Springer; 2008.
16. Cornelis WM. Hydroclimatology of wind erosion in arid and semiarid environments. In: D'Odorico P, Porporato A, editors. *Dryland Ecohydrology.* Netherlands: Springer; 2006.
17. D'Odorico P, Porporato A. Ecohydrology of arid and semiarid ecosystems: an introduction. In: D'Odorico P, Porporato A, editors. *Dryland Ecohydrology.* Netherlands: Springer; 2006.
18. Morin J, Benyamini Y, Michaeli A. The effect of raindrop impact on the dynamics of soil surface crusting and water movement in the profile. *J. Hydrol.* 1981;52(1):321-335.
19. McIntyre DS. Permeability measurements of soil crusts formed by raindrop impact. *Soil Sci.* 1958;85(1):185-189.
20. Chen Y, Tarchitzky J, Brouwer J, Morin J, Banin A. Scanning electron microscope observations on soil crusts and their formation. *Soil Sci.* 1980;130(1):49-55.
21. Assouline S. Modeling the dynamics of seal formation: analysis of the effect of soil and rainfall properties. *Wat. Res. Manag.* 2004;36(1):2341-2349.

22. Watson DA, Laflen JM. Soil strength, slope, and rainfall intensity effects on interrill erosion. *Trans. Am. Soc. Agric. Eng.* 1986;29(1):98-102.
23. Croke BFW, Ticehurst JL, Letcher RA, Norton JP, Newham LTH, Jakeman AJ. Integrated assessment of water resources: Australian experiences. *Wat. Res. Manag.* 2007;21(1):351-373.
24. Issa OM, Trichet J, Defarge C, Coute A, Valentin C. Morphology and microstructure of microbiotic soil crusts on a tiger bush sequence (Niger, Sahel). *Catena.* 1999;37(2):175-196.
25. Issa OM, Valentin C, Rajot JL, Cerdan O, Desprats JF, Bouchet T. Runoff generation fostered by physical and biological crusts in semi-arid sandy soils. *Geoderma.* 2011;167-168:22-29.
26. Morgan RPC, Quinton JN, Smith RE, Govers G, Poesen JWA, Auerswald K, Chisci G, Torri D, Styczen ME. The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. *Eart. Surf. Process. Landf.* 1998;23(1)527-544.
27. Puigdefábregas J. The role of vegetation patterns in structuring runoff and sediment fluxes in drylands. *Eart. Surf. Process. Landf.* 2005;30(1):133-147.
28. Tavares J, Ferreira AJD, Reis EA, Baptista I, Amoros R, Costa L, Furtado AM, Coelho C. Appraising and selecting strategies to combat and mitigate desertification based on stakeholder knowledge and global best practices in Cape Verde Archipelago. *Land. Degrad. Dev.* 2013;25(1):45-57.
29. Stroosnijder L, Moore D, Alharbi A, Argaman E, Biazin B, Van Den Elsen E. Improving water use efficiency in drylands. *Curr. Opin. Envir. Sustain.* 2003;4(1):1-10.
30. Huenchuleo C, Barkmann J, Villalobos P. Social psychology predictors for the adoption of soil conservation measures in Central Chile. *Land Degrad. Dev.* 2012;23(1):483-495.
31. Thapa GB, Yila OM. Farmers' land management practices and status of agricultural land in the Jos Plateau, Nigeria. *Land Degrad. Dev.* 2012;23(1):263-277.
32. Tavares Filho J, Barbosa GMC, Ribon AA. Physical properties of Dystrophic Red Latosol (Oxisol) under different agricultural uses. *Mag. Braz. of Sci. of Soil.* 2010;34(1):925-933.
33. Fao. Food and Agricultura Organization of the United Nations. Evolution of Crop Production, FAOSTAT. Rome: Fao; 2014.
34. García-Ruiz JM. The effects of land uses on soil erosion in Spain: a review. *Catena.* 2010;81(1):1-11.
35. El Kateb H, Zhang H, Zhang P, Mosandl R. Soil erosion and surface runoff on different vegetation covers and slope gradients: a field experiment in Southern Shaanxi Province. *Catena.* 2013;105(1):1-10.
36. Foster GR, Meyer LD, Onstad CA. An erosion equation derived from basic erosion principles. *Trans. Am. Soc. Agric. Eng.* 1976;19(1):678-682.
37. Govers G. Soil erosion process research: A state of the art. Brussel: Paleis der Academien; 1996.
38. Gerits JJP, Lima JLPD, Broek TMWVD. Overland flow and erosion. In: Anderson MG, Burt TP, editors. *Process studies in hillslope hydrology*. Chichester: Journal Willey; 1990.
39. Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Sa_Ouri R, Blair R. Environmental and Economic Costs of Soil Erosion and Conservation Benefits. *Science.* 1995;267(1):1117-1123.
40. Richter G. Bodenerosion: Analyse und Bilanz eines Umweltproblems. Darmstadt: Wissenschaftliche Buchgesellschaft; 1998.

41. Baumann F, He JS, Schmidt K, Kühn P, Scholten T. Pedogenesis, permafrost, and soil moisture as controlling factors for soil nitrogen and carbon contents across the Tibetan Plateau, *Glob. Chang. Biol.* 2009;15(1):3001-3017.
42. Zhao HL, He YH, Zhou RL, Su YZ, Li YQ, Drake S. Effects of desertification on soil organic C and N content in sandy farmland and grassland of Inner Mongolia. *Catena.* 2009;77(1):187-191.
43. Krautzer B, Wittmann H, Peratoner G, Graiss W, Partl C, Parente G. Site-specific high zone restoration in the Alpine Region: The current technological development. *Irdning: Federal Research and Education Centre (HBLFA) Raumberg- Gumpenstein*; 2006.
44. Renard KG, Foster GR, Weesies GA, Porter JP. Rusle: Revised Universal Soil Loss Equation. *J. Soil and Water Cons.* 1991;46(1):30-33.
45. De Roo APJ, Wesseling CG, Ritsema CJ. Lisem: A single-event physically based hydrological and soil erosion model for drainage basins I: theory, input and output. *Hydrol. Process.* 1996;10(1):1107-1117.
46. Ascough JC, Baffaut CM, Nearing AJC, Liu B. The WEPP watershed model: II. Sensitivity analysis and discretization on small watersheds. *St. Joseph: American Society of Agricultural and Biological Engineers*; 1997.
47. Zhang GH. Using ⁷Be measurements to estimate the relative contributions of interrill and rill erosion. *Geomorphology.* 2014;206(1):392-402.
48. Gyssels G, Poesen J, Bochet E, Li Y. Impact of plant roots on the resistance of soils to erosion by water: a review. *Prog. in Phys. Geog.* 2005;29(1):189-217.
49. Stolte J, Liu B, Ritsema CJ, Van Den Elsen HGM, Hessel, R Modelling water flow and sediment processes in a small gully system on the Loess Plateau in China. *Catena.* 2003;54(2):117-130.
50. Mannering JV, Meyer LD. The effects of various rates of surface mulch on infiltration and erosion. *Soil Sci. Soc. of Amer. Proc.* 1963;27(1):84-86.
51. Braidia JA, Cassol EA. Erosion relationships between grooves with the type and the amount of vegetal residue on the soil surface. *Braz. Jour. of Soil Sci.* 1999;23(3):699-709.
52. Cantalice JRB. Flow and erosion in furrows and furrows in different soil surface conditions. *Porto Alegre, Federal Rural University of Rio Grande do Sul*; 2002.
53. Foster GR. Modeling the erosion process. In: Haan CT, Johnson HP, Brakensiek DL, editors. *Hydrologic modeling of small watersheds.* St. Joseph: American Society of Agricultural Engineering; 1982.
54. Laflen JM, Foster GR, Onstad C. Simulation of individual storms soil losses for modeling the impact of soil erosion on cropland productivity. In: El-Swafy SA, Moldenhauer WC, editors. *Soil erosion and conservation.* Ankeny: Soil Conservation Society of America; 1985.
55. Cardoso DP, Silva MLN, Carvalho GJ, Freitas DAF, Avanzi JC. Covering plants in the control of soil, water and nutrient losses due to water erosion. *Braz. Jour. of Agric. and Envir. Eng.* 2012;16(1):632-638.
56. Young RA, Wiersma J. The role of rainfall impact in soil detachment and transport. *Wat. Res. Manag.* 1973;9(6):1629-1636.
57. Gilley JE, Woolheiser D, Mcwhorter D. Interrill soil erosion, Part I. Development of model equations. *Biol. Syst. Eng. Pap. Publ.* 1985;28(1):147-153.

58. Bradford J, Ferris J, Remly P. Interrill soil erosion processes: I. Effect of surface sealing on infiltration, runoff, and soil splash detachment. *Soil Sci. Soc. Am. J.* 1987;51(6):1566-1571.
59. Govers G, Everaert W, Poesen J, Rauws G, De Ploey J, Lautridou JP. A long flume study of the dynamic factors affecting the resistance of a loamy soil to concentrated flow erosion. *Earth Surf. Proc. Land.* 1990;15(4):313-328.
60. Beuselinck L, Govers G, Hairsine P, Sander G, Breynaert M. The influence of rainfall on sediment transport by overland flow over areas of net deposition. *Jour. Hydrol.* 2002;257(1):145-163.
61. Zhang GH, Liu BY, Liu GB, He XW, Nearing MA. Detachment of undisturbed soil by shallow flow. *Soil Sci. Soc. Am. J.* 2003;67(3):713-719.
62. Cochrane TA, Flanagan DC. Detachment in a simulated rill. *Trans. Asae.* 1997;40(1):111-119.
63. Zhang GH, Liu BY, Nearing MA, Huang CH, Zhang KL. Soil detachment by shallow flow. *Trans. Asae.* 2002;45(2):351-357.
64. Poesen J, Nachtergaele J, Verstraeten G, Valentin C. Gully erosion and environmental change: importance and research needs. *Catena.* 2003;50(2-4), 91-133, 2003.
65. Knapen A, Poesen J, Govers G, Gyssels G, Nachtergaele J. Resistance of soils to concentrated flow erosion: a review. *Eart. Sci. Rev.* 2007;80(1):75-109..
66. Nearing MA, West LT, Brown LC. A consolidation model for estimating changes in rill erodibility. *Trans. Asae.* 1988;31(3):696-700.
67. Ghebreiyessus YT, Gantzer CJ, Alberts EE. Soil-erosion by concentrated flow-shear-stress and Bulk-density. *Trans. Asae.* 1994;37(6):1791-1797.
68. Khanbilvardi RM, Rogowski AS. Modeling soil-erosion, transport and deposition. *Ecol. Model.* 1986;33(2-4):255-268.
69. Zheng FL, Huang CH, Norton LD. Vertical hydraulic gradient and run-on water and sediment effects on erosion processes and sediment regimes. *Soil Sci. Soc. Am. J.* 2000;64(1):4-11.
70. Knapen A, Poesen J, Govers G, De Baets S. The effect of conservation tillage on runoff erosivity and soil erodibility during concentrated flow. *Hydrol. Process.* 2008; 22(10):1497-1508.
71. Abrahams AD, Parsons AJ, Wainwright J. Resistance to overland flow on semiarid grassland and shrubland hillslopes, Walnut Gulch, southern Arizona. *Jour. Hydrol.* 1994; 156(1):431-446.
72. Parsons AJ, Abrahams AD, Wainwright J. Responses of interrill runoff and erosion rates to vegetation change in southern Arizona. *Geomorphology.* 1996;14(4):311-317.
73. Wainwright J, Parsons AJ, Abrahams AD. Plot-scale studies of vegetation, Overland flow and erosion interactions: case studies from Arizona and New Mexico. *Hydrol. Process.* 2000;14(16-17):2921-2943.
74. Zhang GH, Liu GB, Tang KM, Zhang XC. Flow detachment of soils under different land uses in the Loess Plateau of China. *Trans. Asabe.* 2008;51(3):883-890.
75. Zhang GH, Tang MK, Zhang XC. Temporal variation in soil detachment under different land uses in the Loess Plateau of China. *Eart. Surf. Proc. Land.* 2009;34(9):1302-1309.
76. Morgan RPC, Quinton JN, Edwards J. Vegetation strategies for combating desertification. MEDALUS II Project 3 Managing Desertification. Contract EV5V-CT92-0165; 1995.

77. Bochet E, Poesen J, Rubio JL. Runoff and soil loss under individual plants of a semi-arid Mediterranean shrubland: Influence of plant morphology and rainfall intensity. *Eart. Sur. Proc. and Landf.* 2006;31(1):536-549.
78. Morgan RPC. Vegetative-based technologies for erosion control. In Stokes A, Spanos JE, Norris, Cammeraat E, editors. *Eco- and ground bio-engineering: The use of vegetation to improve slope stability*. Dordrecht: Springer; 2007.
79. De Baets S, Poesen J, Gyssels G, Knapen A. Effects of grass roots on the erodibility of topsoil during concentrated flow. *Geomorphology*. 2006;76(1):54-67.
80. Pohl M, Alig D, Körner C, Rixen C. Higher plant diversity enhances soil stability in disturbed alpine ecosystems. *Plant Soil*. 2009;324(1):91-102.
81. Jiao J, Zou H, Jia Y, Wang N. Research progress on the effects of soil erosion on vegetation. *Acta Ecol. Sin.* 2009;29(1):85-91.
82. Wainwright J, Parsons AJ. Classics in physical geography revisited. In: Thornes JB, editors. *The ecology of erosion. Progress in Physical Geography*; 2010.
83. Thornes JB. Stability and instability in the management of Mediterranean desertification. In: Wainwright J, Mulligan M, editors. *Environmental Modelling: Finding Simplicity in Complexity*. Chichester: John Wiley; 2004.
84. Zehe E, Sivapalan M. Threshold behaviour in hydrological systems as (human) geo-ecosystems: manifestations, controls, implications. *Hydrol. and Eart. Syst. Sci.* 2009;13(1):1273-1297.
85. Quijas S, Jackson LE, Maass M, Schmid B, Raffaelli D, Balvanera P. Plant diversity and generation of ecosystem services at the landscape scale: expert knowledge assess- 10 ment. *Jour. Appl. Ecol.* 2012;49(1):929-940.
86. Chisholm RA. Scale-dependent relationships between tree species richness and ecosystem function in forests, *Jour. Ecol.* 2013;101(1):1214-1224.
87. Scherer-Lorenzen M. The functional role of biodiversity in the context of global change. In: Coomes DA, Burslem DFRP, Simonson WD *Forests and global change*. Cambridge: Cambridge University Press; 2014.
88. Romero-Diaz A, Belmonte-Serrato F, Ruiz-Sinoga JD. The geomorphic impact of afforestations on soil erosion in Southeast Spain, *Land Degrad. Dev.* 2010;21(1):188-195.
89. Jiao J, Zhang Z, Bai W, Jia Y, Wang N. Assessing the Ecological Success of Restoration by Afforestation on the Chinese Loess Plateau. *Rest. Ecol.* 2012;20(1):240-249.
90. Boer M, Puigdefabregas J. Effects of spatially structured vegetation patterns on hillslope erosion in a semiarid Mediterranean environment: A simulation study. *Eart. Surf. Proc. and Landf.* 2005;30(1):149-167.
91. Bautista S, Mayor AG, Bourakhouadar J, Bellot J. Plant spatial pattern predicts hillslope semiarid runoff and erosion in a Mediterranean landscape. *Ecosystems*. 2007;10(1):987-998.
92. Durán ZVHD, Pleguezuelo CRR. Soil-erosion and runoff prevention by plant covers: A review. *Agron. for Sust. Devel.* 2008;28(1):65-86.
93. Li Y, Shao M. Change of soil physical properties under long-term natural vegetation restoration in the Loess Plateau of China. *Jour. Arid Environ.* 2006;64(1):77-96.
94. Körner C. Mountain biodiversity, its causes and function. *Ambio*. 2004;4(4):11-17.

95. Körner C, Spehn EM. Mountain biodiversity: A global assessment. London: Parthenon Publishing Group; 2002.
96. Vásquez-Méndez R, Ventura-Ramos E, Oleschko K, Hernández-Sandoval L, Parrot JF, Nearing MA. Soil erosion and runoff in different vegetation patches from semiarid Central Mexico. *Catena*. 2010;80(1):162-169.
97. Tengbeh GT. The effect of grass roots on shear strength variations with moisture content, *Soil Tech*. 1993;6(1):287-295.
98. De Baets S, Poesen J, Reubens B, Wemans K, De Baerdemaeker J, Muys B. Tensile strength and root distribution of typical mediterranean plant species and their contribution to soil shear strength. *Plant Soil*. 2008;305(1):207-226.
99. Carvalho DF, Cruz ES, Pinto MF, Silva LDB, Guerra JGM. Rainfall characteristics and erosion losses under different soil management practices. *Braz. Jour. of Agric. and Envir. Eng*. 2009;13(1):3-9.
100. Ben-Hur M, Fernandez C, Sarkkola S, Cerezal JCS. Overland flow, soil erosion and stream water quality in forest under different perturbations and climate conditions. In: Bredemeier M, Cohen S, Godbold DL, Lode E, Pichler V, Schleppi P, editors. *Forest Management and the Water Cycle*. Netherlands: Springer; 2011.
101. Wagenbrenner JW, Macdonald LH, Rough D. Effectiveness of three post-fire rehabilitation treatments in Colorado Front Range. *Hydrol. Proces*. 2006;20(1):2989-3006.
102. Ferreira ADJ, Coelho COA, Ritsema CJ, Boulet AK, Keizer JJ. Soil and water degradation processes in burnt areas: lessons learned from a nested approach. *Catena*. 2008;74(1):273-285.
103. Shakesby RA, Doerr SH. Wildfire as a hydrological and geomorphological agent. *Eart. Sci. Rev*. 2006;74(1):269-307.
104. Bryan RB. Soil erodibility and processes of water erosion on hillslope. *Geomorphology*. 2000;32(1):385-415.
105. Hales TC, Ford CR, Hwang T, Vose JM, Band LE. Topographic and ecological controls on root reinforcement. *Jour. Geoph. Res*. 2009;114(1):1-17.
106. Prosser IP, Dietrich WE, Stevenson J. Flow resistance and sediment transport by concentrated overland flow in a grassland valley. *Geomorphology*. 1995;13(1):71-86.
107. Haynes RJ, Beare MH. Influence of six crop species on aggregate stability and some labile organic matter fractions, *Soil Biol. Bioch*. 1997;29(1):1647-1653.
108. Degens BP. Macro-aggregation of soils by biological bonding and binding mechanisms and the factors affecting these: A review. *Austr. Jour. Soil Res*. 1997;35(1):431-459.
109. Moreno-Espíndola IP, Rivera-Becerril F, De Jesús FGM, De León-González, F. Role of root-hairs and hyphae in adhesion of sand particles, *Soil Biol. Bioch*. 2007;39(1):2520-2526.
110. Amezketa E. Soil aggregate stability: a review. *Jour. Sust. Agron*. 1999;14(1):83-151.
111. Morel JL, Habib L, Plantureux S, Guckert A. Influence of maize root mucilage on soil aggregate stability, *Plant Soil*. 1991;136(1):111-119.
112. Oades JM. Soil organic matter and structural stability: mechanisms and implications for management, *Plant Soil*. 1984;76(1):319-337.
113. Watt M, McCully ME, Canny MJ. Formation and stabilization of rhizosheaths of *Z. mays* L. *Plant Physiol*. 1994;106(1):179-186.

- 696
697 114. Mccully ME. Roots in soil: unearthing the complexities of roots and their rhizospheres, *Ann. Rev.*
698 *Plant Phys.* 1999;50(1):695-718.
699
- 700 115. Pojasok T, Kay BD. Effect of root exudates from corn and brome grass on soil structural stability.
701 *Can. Jour. Soil Sci.* 1990;70(1):351-362.
702
- 703 116. Walker TS, Harsh PB, Grotewold E, Vivanco JM. Root exudates and rhizosphere biology. *Plant*
704 *Physiol.* 2003;132(1):44-51.
705
- 706 117. Stokes A, Atger C, Bengough AG, Fourcaud T, Sidle RC. Desirable plant root traits for protecting
707 natural and engineered slopes against landslides. *Plant Soil.* 2009;324(1):1-30.
708
- 709 118. Bertin C, Yang X, Weston L. The role of root exudates and allelochemicals in the rhizosphere.
710 *Plant Soil.* 2003;256(1):67-83.
711
- 712 119. Macleod CJA, Binley A, Hawkins SL, Humphreys MW, Turner LB, Whalley WR, Haygarth PM.
713 Genetically modified hydrographs: what can grass genetics do for temperate catchment hydrology?,
714 *Hydrol. Process.* 2007;21(1):2217-2221.
715
- 716 120. Bronick CJ, Lal R. Soil structure and management: a review. *Geoderma.* 2005;124(1):3-22.
717
- 718 121. Quinton JN, Edwards GM, Morgan RPC. The influence of vegetation species and plant
719 properties on runoff and soil erosion: results from a rainfall simulation study in south east Spain. *Soil*
720 *Use Man.* 2002;13(1):143-148.
721
- 722 122. Meek BD, Rechel EA, Carter LM, De Tar WR. Changes in infiltration under alfalfa as influenced
723 by time and wheel traffic. *Soil Sci. Soc. Am. Jour.* 1989;53(1):238-241.
724
- 725 123. Mitchell AR, Ellsworth TR, Meek BD. Effects of root systems on preferential flow in swelling soils.
726 *Comm. in Soil Sci. and Plant Anal.* 1995;26(1):2655-2666.
727
- 728 124. Archer NAL, Quinton JN, Hess TM. Below-ground relationships of soil texture, roots and
729 hydraulic conductivity in two-phase mosaic vegetation in South-east Spain. *Jour. Arid Envir.*
730 2002;52(1):535-553.
731
- 732 125. Devitt DA, Smith SD. Root channel macropores enhance downward movement of water in a
733 Mojave Desert ecosystem. *Jour. Arid Envir.* 2002;50(1):99-108.
734
- 735 126. Bauhus J, Messier C. Soil exploitation strategies of fine roots in different tree species of the
736 southern boreal forest of eastern Canada. *Can. Jour. Fores. Res.* 1999;29(1):260-273.
737
- 738 127. De Baets S, Poesen J, Knapen A, Galindo P. Impact of root architecture on the 23 erosion-
739 reducing potential of roots during concentrated flow. *Eart. Surf. Proc. Land.* 2007;32(9):1323-1345.
740
- 741 128. Poesen J, Nachtergaele J, Verstraeten G, Valentin C. Gully erosion and environmental change:
742 importance and research needs. *Catena.* 2003;50(2-4):91-133.
743
- 744 129. Wischmeier WH. Estimating the soil loss equation's cover and management factor for
745 undisturbed areas. *Pres. and Prosp. Tech. for Pred. Sed. Yiel. and Sour.* 1975:118-124.
746
- 747 130. Dissmeyer GE, Foster GR. A Guide for Predicting Sheet and Rill Erosion on Forest Land, 4.
748 Washington: USDA-Forest Service; 1980.
749