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A Review on Rill Erosion Process and Its Influencing Factors

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Abstract: Rills are frequently observed on slope farmlands and rill erosion significantly contributes to sediment yields. This paper focuses on reviewing the various factors affecting rill erosion processes and the threshold conditions of rill initiation. Six factors, including rainfall, runoff, soil, topography, vegetation and tillage system, are discussed. Rill initiation and network are explored. Runoff erosivity and soil erodibility are recognized as two direct factors affecting rill erosion and other types of factors may have indirect influences on rill erosion through increasing or decreasing the effects of the direct factors. Certain conditions are necessary for rill initiation and the critical conditions are different with different factors. Future studies should be focused on 1) the dynamic changes of rill networks; 2) the combined effect of multiple factors; and 3) the relationships of threshold values with other related factors.

Keywords: rill initiation; rill erosion; rill network; critical condition

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1 Introduction

Soil erosion is one of the most important land degradation problems worldwide (Vrieling, 2006). Basically, there are four main types of erosion: sheet, rill, gully and in-stream erosion (Merritt *et al*., 2003). Rill erosion is usually identified as a series of little channels or rills up to 30 cm deep that can be obliterated by cultivation (Cerdan *et al*., 2002). As intermediate stage between overland and gully erosion, theories for soil detachment by rill erosion are different with that by interrill erosion (Foster and Meyer, 1972; Romero *et al*., 2007). The loss of the topsoil and nutrients caused by rill erosion will reduce soil productivity, and the deposition of off-site sediments can bring sedimentation and water-quality deterioration in streams and reservoirs. Concentrated flow is one of the main sources of soil detachment energy in rills, while raindrops play more significant roles for interrill erosion (Bradford *et al*., 1987; Owoputi and Stolte, 1995; Govers *et al*., 2007). As soil erodibility and transport capacity by concentrated flow is much greater than that caused by rainfall drops, rills have induced quantum leap on the amount of slope erosion (Auerswald *et al*., 2009). For example, Meyer *et al*. (1975) found that the amount of soil erosion increased two times after the appearance of rills in field spots with silt soil. On the Loess Plateau of China, the contribution of rill erosion can be up to more than 70% of slope erosion and about 50% of the total erosion (Li *et al*., 2010). Kimaro *et al*. (2008) found that rill erosion is more important than interrill erosion and accounts for an average of 58% of the total soil loss in the mountainous areas of East Africa.

An understanding of rill erosion process is not only

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significant for the prevention of soil erosion in slope farmlands, but also of importance to soil erosion prediction models. During the past 50 years, qualitative and quantitative investigations have been conducted on rill initiation, rill networks, and the impacts of different factors on rill formation (Bryan and Poesen, 1989; Brunton and Bryan, 2000; Rejman and Brodowski, 2005; Bai *et al*., 2007; Bruno *et al*., 2008; Luo *et al*., 2012; Wang and Shangguan, 2012; Zhang *et al*., 2012). In addition, various approaches, including laboratory experiments, field experiments, satellite remote sensing (Vrieling, 2006), digital photogrammetry (Gessesse *et al*., 2010; Huo *et al*., 2011), have been developed to describe and predict sediment detachment and transport in rills (Hessel and Jetten, 2007; Wirtz *et al*., 2012). Moreover, a considerable number of reviews have been published. For example, Govers *et al*. (2007) had a thorough review on the relationship between experiments, modeling and field observations on rills. Unfortunately, a discrepancy exists among the current investigations on the rill development and its responses to different controlling factors. Previous investigations put much attention on the impact of single factors on rills. However, there has been a lack of studies on the combinations and interactions of different factors. The intrinsic mechanisms of rill erosion are still unclear due to its complexity, especially under different physical conditions, coupling with the influences of complex human actions. The objective of this paper is to provide an overview of investigations on: 1) development processes and morphology of rills; 2) impacts and interactions of different factors; and 3) threshold conditions for rill initiation.

2 Rill Initiation and Rill Networks

2.1 Rill initiation

Rill erosion process includes detachment, entrainment, and transport of soil particles (Yao *et al*., 2008). The results of Huo *et al*. (2011) indicated that the development processes of rills can be summarized as five stages: knickpoints, head cut extension, intermittent rill, continuous rill and rill networks. Wang (1998) divided the rill erosion process into four sub-stages: 1) downward incision and horizontal development along the wetted perimeter of a rill; 2) local erosion by the scarps in a rill; 3) collapses of rill walls; and 4) lateral migrations of a rill. The viewpoints about the reasons for the initiation and development of rill erosion are inconsistent due to the complexity and randomness of rills and the limitation of different experimental conditions. The results of some investigations indicated that soil surface crust is of significance to the initiation of rills (Remley *et al*., 1989; Singer and Le Bissonnais, 1998; Ding *et al*., 2001; Cai *et al*., 2004; Cheng *et al*., 2005).

On one hand, soil crust can sharply reduce soil infiltration and thus increase runoff erosivity to trigger rill erosion (McIntyre, 1958; Ding *et al*., 2001; Hussein *et al*., 2010). On the other hand, soil crust can hinder rill erosion through increasing soil shear strength and reducing the detachment of soil (Cai *et al*., 2004; Cheng *et al*., 2005). Slope erosion experiments under rainfall simulation showed that soil surface sealing or crust could increase the sediment yield of rill erosion during the first four rainfall experiments, but hinder the development of rill erosion thereafter (Chen *et al*., 2011).

Unfortunately, the contribution of these two functions to rill development and its sediment yield is not clear. However, some researchers agreed that interflow plays more important roles than soil surface crust in rill initiation (Loch *et al*., 1987; Beven, 1996; Liu *et al*., 2004). When soil water content reaches the point of saturation under rainfall, interflows are concentrated and exit to the soil surface at the lower part of slope, and channels are thus developed along the exit of interflows. At the same time, knickpoints occur at the top of the channels following the collapse of the top soil and then rills are developed (Liu *et al*., 2004).

It is a general agreement that rills are developed by concentrated flow (Consuelo *et al*., 2007). However, the results of some studies showed that rills are triggered by overland flows (Li *et al*., 2002; Ding *et al*., 2003). Overland flows move in the form of roll waves under certain circumstances, which is influenced by the magnitudes of runoff discharge and slope gradient (Ding *et al*., 2001). The superimposition of rolling waves results in the increase of local water depth in the processes of flowing from upper slope to the lower slope. And this leads to the surge of the erosion shear stress. When the shear stress is greater than soil resistance force, erosion occurs and ultimately results in the formation of rill headcut (Ding *et al*., 2003).

It is necessary to discuss the relationship between rill and interrill erosion, the two important components of slope erosion. Differing from the detachment and transport of soil particles by concentrated flow in rills, the detachment of soil particles is mainly caused by raindrops and the transport energy is mainly from overland flow for interrill erosion (Consuelo *et al.*, 2007). It is a common agreement that hydraulic characteristics of overland flow are significantly different from channel hydraulics (Savat, 1977). Comparing subcritical rill flow with perimeter roughness elements entirely submerged by the viscous sub-layer, overland flow is characterized as supercritical and discontinuous, with variable depths and roughness elements penetrating the viscous sublayer (Bryan, 2000). It is reported that soil erosion processes are sediment selective, and the enrichment of clay and silt-sized particles in eroded materials is a general observation (Asadi *et al.*, 2011). In comparison to the selectivity of fine particles by interrill erosion, rill erosion is less selective (Shi *et al.*, 2012b). It is generally agreed that fine particles (< 0.054 mm) is more easily removed by rill erosion, whereas medium to large-sized particles are increasingly important in sediment transport after the development of rills on hillslopes (Shi *et al.*, 2012a). The selective sediment transport by interrill erosion is mainly attributed to the insufficient transport capacity of overland flow (Parsons *et al.*, 1991). Normally, interrill erosion dominates on the upper part of the slope, while rill erosion is much more dependent on slope length and steepness (Govers and Poesen, 1998). Knowledge of the contribution of rill and interrill processes to total soil loss is important for both prediction models and practical interests. However, it is inhibited by the scarcity of available field data that permit the separation of rill and interrill erosion (Govers and Poesen, 1998; Kimaro *et al.*, 2008). It was observed that the importance of rill erosion decreased with time, mainly due to an increase in permeability of the interrill with time though it is not a general phenomenon (Mtkawa *et al.*, 1987). However, the opposite results that the relative importance of interrill erosion decreases with time were presented by other researchers (Govers and Poesen, 1998). Although controversial results exist in the relative importance of interrill/rill erosion with time, there are general agreements on the significant roles of the transition from interrill to rill processes on the erosion rates and the geomorphic evolution of hillslopes (Bryan, 1987). Therefore, the investigations on the threshold conditions are become more necessary (Bryan, 2000).

2.2 Rill networks

Rill networks are changing rapidly along with sediment yield processes, which is a distinct feature of rill erosion. Rill length, rill depth and rill width are three indicators to reflect rill morphology. The main driving forces for an increase in length, depth and width of rill are headward erosion, flow shear and collapse of channel wall, respectively (Huo *et al.*, 2011). The headward erosion can increase the rill length, and the rill depth is mainly limited by the elevation of rill base and shows no significant relationships with slope gradients (Ni *et al.*, 2002). The results of both measurements and theoretical deductions have proved that there is a close relationship between rill length and rill volume. Thus, rill length is recognized as a severity index of rill erosion process. The results of the studies showed that the detachment capacity of rills is significantly influenced by rill length. In the upper part of a rill, water flow can erode the wetted perimeter and transport the eroded particles. In the lower part, water flow can only transport the particles coming from the upstream without scouring the rill perimeter (Wirtz *et al.*, 2012). In the past, the investigations were prone to using theoretical models for the deduction of rill networks, of which self-organization models are normally employed (Govindaraiu and Kavvas, 1994; Favis-Mortlock, 1998). The simulation results were usually verified indirectly by using routine observation data of sediment and runoff yield. However, the direct verification was hindered by the scarcity of the observations on the dynamics of rill networks, due to the limitation in measurement technologies. Following the rapid development of photogrammetry, quantitative description and simulation of rill networks become more feasible and focused, both in laboratory and in field (Gessesse *et al.*, 2010; Pérez-Cabelloa *et al.*, 2012). Berger *et al.* (2010) calculated digital elevation models by using photogrammetry for initiation and evolution of rill networks and found that energy expenditure can be well used for the measurement of rill network self-organization with time. Dynamics, influencing factors, and responses of runoff and sediment yield to the rill networks have become the forefront focuses of rill erosion studies. In addition, considering the mutual feedback of rill flows and rill network evolution should be taken into consideration in the prediction models (Lei *et* *al*., 1998; 2001; Liu *et al*., 2004).

3 Influencing Factors of Rill Erosion

Many factors, including rainfall, runoff, soil, topography, vegetation, and tillage system have great impacts on rill development and sediment yield. The results of some investigations indicated that rill erosion is directly controlled by combined actions of runoff and soil. Other factors may have indirect influences on rill erosion through increasing or decreasing the effects of the direct factors (Li *et al*., 2010; Li *et al*., 2011; Wirtz *et al*., 2012). The relationships of different factors are shown in Fig. 1.

3.1 Rainfall

The functions of rainfall on slope erosion are mainly reflected by the raindrop impacts. Rainfall erosivity is defined as the potential energy on soil erosion, and is closely related with many parameters, such as rainfall intensity, rainfall amount, rainfall duration, *etc*. (Sun *et al*., 2011). Investigations have been made to establish complex indices characterizing rainfall erosivity, including EI_{30}, EI_{10}, EI_{15}, EI_{60}, $E_{60}I_{60}$, $E_{60}I_{10}$, $E_{60}I_{30}$, PI_{10}, PI_{30}, (E is the total kinetic energy of individual rainfall; I_{30} is the maximum rainfall intensity during the continual 30-minute of individual rainfall; I_{10} is the maximum rainfall intensity during the continual 10-minute of individual rainfall; I_{15} is the maximum rainfall intensity during the continual 15-minute of individual rainfall; I_{60} is the maximum rainfall intensity during the continual 60-minute of individual rainfall; E_{60} is the kinetic energy exported by the maximum rainfall intensity during the continual 60-minute of individual rainfall; P is the rainfall amount of individual rainfall) *etc*. (Sun *et al*., 2011). Römkens *et al*., (2002) found that the amounts of rill erosion are different with different rainfall sequences under laboratory experiments. Close correlations were observed between the increase of soil losses by rill and the increase of rainfall kinetic energy (Wang, 1998). Rainfall intensity had greater effects on rill dynamics and soil losses than slope with the treatments considered (Berger *et al*., 2010).

3.2 Runoff

Runoff can erode the slope and move sediments directly. Thus, it is easier to investigate the functions of runoff on rill erosion from the point of view of runoff flow dynamics, including flow discharge rate (Meyer and Wischmeier, 1969), flow pattern (Foster *et al*., 1984), flow velocity (Guy *et al*., 1987; Govers, 1992), flow depth (Nearing *et al*., 1991), flow resistance (Foster *et al*., 1984; Abrahams and Parsons, 1994) and flow shear stress (Nearing *et al*., 1997). Great efforts have been

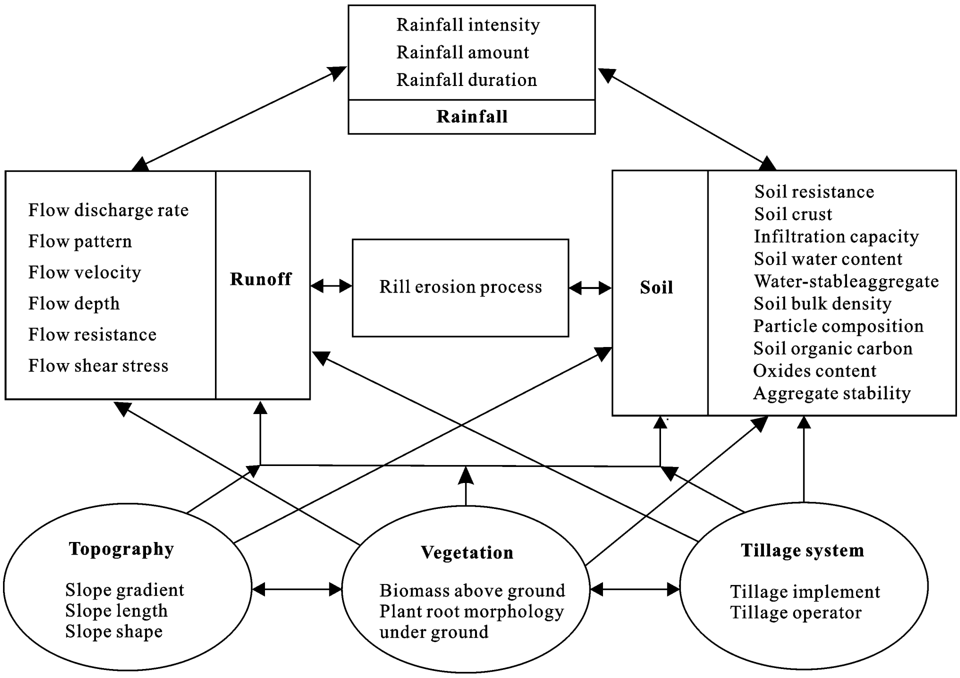

Fig. 1 Relationships of influencing factors on rill erosion process

made to predict the amount of rill erosion by using flow hydraulic parameters, such as Reynolds number and Froude number (Govers and Rauws, 1986; Nearing *et al.*, 1989). It has been discussed that these simulations are derived from the sediment delivery of river flows and are, to some extent, flawed, due to the distinct characteristics of rill flows from river flows (Han *et al.*, 2011). When rills emerge, hydraulic characteristics of runoff flow change significantly, and thus rill flows are different from both overland flows and river flows (Liu *et al.*, 2004). Due to the complexity of rill flows, contradictory results have been obtained. For example, Foster *et al.* (1984) found that rill flow velocity is influenced by flow discharges and slope gradients, while other researchers found that rill flow velocity is independent of slope gradients because of a feedback between rill bed morphology and flow conditions (Govers, 1992; Nearing *et al.*, 1999). Moreover, the interaction of rainfall and runoff on rill erosion should not be overlooked. The results of some investigations indicated that raindrops can affect the overland flow characteristic in various ways, such as inputting dynamic energy to runoff flow (Li *et al.*, 2010), changing the flow pattern (Emmett, 1978), increasing the runoff flow resistance (Yoon and Brater, 1962). Nevertheless, Consuelo *et al.* (2007) thought that flow characteristics and soil properties had larger effects on rill erosion than raindrops. Still, the authors of this article agreed that Runoff erosivity is the direct driving force of rill erosion.

3.3 Soil

Soil has complex impacts on rill erosion through many aspects, such as soil resistance, soil crust, infiltration capacity, soil water content, *etc*. Generally, the susceptibility of soil to erosion agents is defined as soil erodibilty, which is closely related with a range of soil properties, including soil physical properties, chemical properties, soil texture and structure (Vireling, 2006). The physical properties of soil, including water-stable aggregates, soil bulk density, particle composition and soil water content, may impact rill erosion through changing soil infiltration capacity and soil shear strength (Li *et al.*, 2010). And soil organic carbon content and oxides contents may impact soil erodibility through changing soil tightness (Emmett, 1978). For water erosion prediction models, soil erodibility factor is either determined directly from soil loss data obtained from time-consuming and costly experimentation or indirectly from easily measured soil properties, including soil texture, cohesion strength, soil shear strength, clay content and aggregate stability (Yan *et al.*, 2008). For example, Han *et al.* (2009) found that > 0.5 mm water-stable aggregates and soil organic carbon content could be used as soil erodibility indices. While, Cai *et al.* (2004) found close relationships between < 0.25 mm water-table aggregates and gross of runoff and sediment yield. They selected the degree of aggregate dispersibility and the ratio of collapsing rate to infiltration rate as two indices to predict the possibility of the occurrence of rill erosion. Zheng (1998) also revealed significant correlations between water-stable aggregates and rill erosion amounts. The results of Young and Onstad (1982) indicated that both soil organic carbon content and soil aggregate structure have significant influences on rill development. The results of some investigations indicated that soil shear strength can be used as an indicator of soil erodibility (Nearing and Bradford, 1985).

Some researchers thought that using aggregate stability as soil erodibility factor is simpler and more feasible for erosion prediction models (Dimoyiannis *et al.*, 2006; Yan *et al.*, 2010). Both positive and negative correlations between aggregate stability and soil erosion have been reported, largely because these results are mainly obtained from empirical information without considering the different models of aggregate breakdown under different initial conditions (Fox and Le Bissonnais, 1998; Yan *et al.*, 2008).

However, because of complex processes involved in the aggregate breakdown, currently no general agreement exists in the theory and measurement of the aggregate breakdown and its relationship to crust and erosion (Le Bissonnais, 1996). For example, the results of Emerson and Greenland (1990) indicated that slaking and dispersion are predominant controlling processes of aggregate breakdown. However, Nearing and Bradford (1985) found that aggregate breakdown is mainly impacted by raindrops. Le Bissonnais (1996) gave a thorough review on the previous studies on the measurement and mechanisms of aggregate breakdown. He concluded that the aggregate breakdown is resulted from four kinds of processes, including slaking, micro-craking, raindrop impacts and physical-chemical dispersion. Slaking is mainly caused by the compression of entrapped air during wetting; hysico-chemical dispersion is mainly caused by the reduction of the attractive forces between colloidal particles while wetting; and dispersion is mainly caused by elementary particles rather than micro-aggregates (Le Bissonnais, 1996). The breakdown of unstable aggregates results in pore collapse, finer particles and microaggregates, which plays significant roles in soil erosion and leads to deterioration of the soil structure (Levy and Miller, 1997; Yan *et al*., 2010). Yan *et al.* (2008) thought that aggregate stability index, incorporating the main mechanisms of aggregate breakdown, could be taken as a substitution for interrill erodibility in prediction model. Shi *et al.* (2010) pointed that soil erosion for both disturbed and undisturbed samples of Ultisols from subtropical China is highly correlated with a new aggregate stability index, K_a, which takes a consideration of aggregate stability in relation to the simultaneous processes of wetting and raindrop impacts. Generally, soil erodibility is another direct driving force of rill erosion.

3.4 Topography

Topography plays significant roles on slope rills and related sediment yield, including the effects of slope gradient, slope length and slope shape. Statistical analyses have been used to determine the effect of slope steepness on soil erosion prediction models (McCool *et al*., 1987; 1993). It is indicated that relationships between slope gradient and soil erosion are changed when certain thresholds of slope steepness reach (Liu *et al*., 1994). The results of many investigations showed that an increase of slope gradient can lead to an increase in the amount of rill erosion (Liu *et al*., 1994; Wang, 1998; Berger *et al*., 2010). Typically, power function models are best fitted for the relationship between slope gradient and the amount of soil erosion, with a power index higher than 1 or even more than 2 (Gerard, 1991; Li *et al*., 2010). However, the relationship is inversed when the slope gradient exceeds certain thresholds (Liu *et al*., 2004). For example, Yair and Klein (1973–1974) found that the increase of the slope gradient can reduce the amount of soil erosion under their experimental conditions. Nevertheless, it was observed that slope gradients have no influences on rill flow velocity (Govers, 1992; Nearing *et al*., 1999). To some extent, slope gradients may have direct impacts on runoff erosivity, percolation and soil erodibility, and thus indirectly affect the development of rills (Li *et al*., 2010). Power functions can be used for the relationship between slope length and the amount of soil loss, with a power index less than 1. It suggests that the role of slope length is less important than that of slope gradient (Zingg, 1940; Li *et al*., 2010). It was observed that the amount of soil loss shows fluctuating characteristics at different sites along very long slopes (Fan *et al*., 2005). The increase degree of runoff discharge with the increase of slope length is mainly conditioned by the hydrological connectivity, and thus the influencing degrees are different (Govers *et al*., 2007).

Slope shapes, usually including uniform slope, concave slope and convex slope, are the combinations of different slope lengths and slope gradients. Therefore, slope shapes have important impacts on rill patterns, rill distribution, rill density, sediment yield and runoff production (Rieke-Zapp and Nearing, 2005). The results of some investigations indicated that maximum soil displacement on concave slopes took place in the upper one-third of the 75-ft long plot, while maximum soil displacement occurred about three-fourths of the plot on convex slope (Young and Mutchler, 1969). Rieke-Zapp and Nearing (2005) pointed that the sediment yields from uniform, nose and convex-linear slopes are more than those from concave-linear and head slopes. Nevertheless, Yu and Wei (2010) found that the sediment concentrations of flows are following the order: concave slope > convex slope > uniform slope. Further studies on the effects of slope gradients and slope length should be conducted to explain the inconsistent results of the past investigations.

3.5 Vegetation

Frequently, a cover and management factor (*C*-factor) is used to account for the functions of vegetation in assessment models of soil erosion (Vrieling, 2006). Vegetation restoration has been extensively applied to soil and water conservation because it can reduce rainfall erosivity, runoff discharge and flow velocity, and increase soil infiltration, soil anti-erodibility and soil stability (Yu *et al*., 2012). The results of the investigations indicated that soil erosion decreases with the increase of vegetation coverage in the Loess Plateau of China (Yu *et al*., 2012). Zheng *et al.* (2007) indicated that vegetation reduces sediment yield only by reducing runoff volume, which results in approximately the same sediment-reduction as runoff-reduction. Woo *et al.* (1997) thought that vegetation growth can help reduce runoff and decrease sediment yield through different processes: 1) intercepting rainfall and increasing evaporation; 2) increasing infiltration by plant roots and cracks in soil; and 3) increasing resistance to flow by vegetation growth.

Besides the impacts of above ground biomass on soil erosion, plant root morphology underground also plays significant roles in slope stabilization and erosion control (Gyssels and Poesen, 2003). Thus a lot of attention has been paid to the contribution of plant roots to soil erosion and thorough reviews have been provided in recent years (Nilaweera and Nutalaya, 1999; Gyssels *et al.*, 2005; Reubens *et al.*, 2007). Generally, the mechanisms of plant roots impacts on soil erosion can be classified as either hydrological or mechanical functions (Nilaweera and Nutalaya, 1999). For the hydrological aspect, plant roots tend to increase soil surface roughness and thus increase the capacity of soil infiltration (Reubens *et al.*, 2007). However, it can also lead to higher landslide risks with the increase of seepage pressure due to the higher water table by plant roots. The overall balance of hydrological effects is difficult to assess. For the mechanical aspect, plant roots increase soil strength and reduce the susceptibility of the soil to rill erosion through many functions, such as penetrating the soil mass, binding soil particles (Prosser *et al.*, 1995). Overall, plant roots have significant impacts on soil erodibility, which can be further influenced by roots architectural characteristics, such as fine or coarse roots, woody and non-woody species (Nilaweera and Nutalaya 1999; Reubens *et al.*, 2007). It was observed that the coarse roots have less effectiveness in increasing soil strength (Reubens *et al.*, 2007). De Baets *et al.* (2006) found that Hill curve is the best model to fit the relationship of relative soil detachment rates and root density as well as root length density. They also found that the decrease of the relative soil detachment caused by increasing roots is much higher than that of plant cover. Based on their observations, they assumed that roots play more effective roles in reducing rill erosion than shoots. Gyssels *et al.* (2005) also pointed that vegetation cover plays more effective roles in controlling splash and interrill erosion, while roots play more effective roles in rills and ephemeral gully erosion. In general, the current knowledge of root morphology and its impact on soil erosion is still rather limited due to the difficulties of measuring root system characteristics (Gyssels *et al.*, 2005; Reubens *et al.*, 2007).

3.6 Tillage system

Many tillage behaviors have impacts on the rill erosion process on cultivated lands (Lobb and Kachanoski, 1999). Tillage implement, such as the type of equipments and cutting tools, can change soil situations and has the potential to trigger rills (Lindstrom *et al.*, 1990). Tillage operations, including tillage frequency, tillage speed and depth, have impacts on rill erosion process through changing the soil infiltration, runoff discharge and soil erodibility (Li *et al.*, 2007; Li *et al.*, 2010). Earlier investigations were focused on the effects of primary tillage implements, such as mould board plough and chisel plough, and now attentions are paid to the effects on rill erosion caused by the secondary tillage and seeding implements (Lindstrom *et al.*, 1992; Li *et al.*, 2007). The results of Li *et al.* (2007) indicated that the erosivity caused by light-cultivator is much lower than that by deep-tiller. Investigations should be further conducted to explain the influences of the sequence of tillage operations on the development of rill erosion.

3.7 Interactions of different factors

As the rill initiation and rill networks are driven by stochastic processes, some laboratory experiments have been conducted to find the relationships among different influencing factors of rill erosion, such as rainfall, runoff, soil, slope length, slope gradient, vegetation (Bryan and Poesen, 1989; Nearing *et al.*, 1991; Wirtz *et al.*, 2012). For example, Bryan and Posen (1989) analyzed the relationship between slope length, percolation, runoff and rill development. They found that runoff is affected by the complex processes of rainfall excess, slope length, surface sealing, rill development and headcut incision. Giménez *et al.* (2004) indicated that bed roughness increases with slope gradients whereas flow velocity decreases until a threshold hydraulic condition reaches. Li *et al.* (2011) found that runoff characteristics indices are positively correlated with rainfall intensity, slope gradient and slope length. However, sediment concentration is mainly determined by rainfall intensity and slope gradient. Generally, the investigations of the effects of multi-factors on rill erosion have not been conducted as extensively as those of single factor in the past. Combinations and interactions of different factors and their impacts on rill initiation and rill networks need further investigations.

4 Critical Conditions of Rill Erosion

The critical conditions for rill initiation have been investigated by many researchers. The idea of critical condition for rill initiation was first conceptualized by Horton (1945). Kirkby (1978) defined the threshold for incipient rills as 'when duration of runoff exceeds this point in time, rill processes will dominate over interrill processes and rill initiation may take place' (Yao *et al.*, 2008).

4.1 Critical hydraulic conditions

Great efforts have been made to find critical hydraulic conditions for rill initiation. Usually, hydraulic indices include Reynolds number (R_e), Froude number (F_r), runoff discharge, runoff shear velocity, runoff energy, *etc*. Savat and De Ploey (1982) found the threshold conditions for rill initiation as:

$$F_{rc} > 1 + 0.0035d \tag{1}$$

where F_{rc} is the critical Froude number; d is the median diameter of sediments.

However, Zhang and Yasuhiro (1998) indicated that the threshold hydraulic conditions for rill initiation should fit equations (2) and (3) simultaneously, and the critical runoff conditions are closely correlated with slope gradient.

$$F_{rc} > 1 \tag{2}$$

$$q_c = 0.8574(\sin\theta)^{-7/6} \tag{3}$$

where q_c is the critical runoff discharge; and θ is the slope gradient.

Some researchers did not agree Froude number as proper indicator for the threshold condition of rill initiation. For example, Lei and Tang (1998) compared three indicators (Froude number (F_r), Reynolds number (R_e) and runoff cross section energy (E)) and concluded that Reynolds number is more appropriate to describe the threshold conditions of rill initiation, and the critical hydraulic conditions should meet the following conditions:

$$R_e \geq 1.486 \tag{4}$$

$$F_{rc} \geq 6.51 \tag{5}$$

$$E \geq 1.387 \text{ cm} \tag{6}$$

The results of some investigations indicated that flow shear stress and flow shear velocity are good indicators to describe the critical hydraulic conditions of rill initiation. Nearing *et al.* (1991) found that critical flow shear stresses range from 0.5 Pa to 2 Pa. Rauws and Govers (1988) concluded that critical flow shear velocities are in a range of 3 cm/s to 3.5 cm/s. Meanwhile, they also took a consideration of soil properties with flow conditions, and found the threshold flow shear velocity is closely correlated with the surface saturated viscosity (Equation (7)):

$$V_{cr} = 0.89 + 0.56C \tag{7}$$

where V_{cr} is the threshold flow shear velocity for rill initiation (cm/s); and C is the surface saturated viscosity (kPa).

Cai (1998) also found a linear correlation between the threshold flow kinetic energy (E_{wr}) and soil shear strength (K_τ), as:

$$E_{wr} = 1.27 + 0.28K_\tau \tag{8}$$

Some researchers investigated the threshold hydraulic values using flow energy. For example, Ding *et al.* (2003) pointed that energy expenditure can be used as a critical index for rill initiation, and rills occur when the energy expenditure exceeds 7.38 J.

4.2 Critical topographic conditions

The results of many investigations indicated that threshold topographic conditions exist. Savat and De Ploey (1982) summarized a number of relevant articles and found that the critical slope gradients range from 2° to 3° for the European loam agricultural lands and from 6° to 12° for sandy soil. Cai (1998) obtained a good correlation between critical slope gradient (A_c) and soil shear stress (K_τ), as:

$$A_c = -16.16 + 2.84K_\tau \tag{9}$$

Yang *et al.* (2008) calculated the critical slope gradient for rill initiation based on sediment dynamics:

$$\partial\left(\frac{q^{0.25}J^{0.026}}{0.68V_C}\right)/\partial\beta = 0 \tag{10}$$

where q is the unit width flux, J is the gradient of rills, V_C is the initiation sediment velocity of rills, β is the slope gradient. Thus, the critical slope gradient of rill initiation is not a fixed value, and is a function of soil properties. The critical slope gradients calculated by

Yang *et al*. (2008) range from 21.3° to 50.4°.

The critical slope length of rill initiation refers to the minimum slope length for the conversion from sheet flow to rill flow, which supplies enough flow distance for runoff to make it obtain enough power and energy to trigger rills (Li *et al*., 2010). The results of the investigations showed that the critical slope lengths for rill initiation exist (Zheng, 1989; Yao *et al*., 2008). Yao *et al.* (2008) approved that the critical slope length decreases with the increase of slope gradient and rainfall intensity. Comparing to rainfall intensity, slope gradient plays more significant roles. Zheng (1989) found a non-linear relationship between the critical rill length and slope gradient:

$$L_C = aJ^2 + bJ + c \tag{11}$$

where L_C is the critical slope length; J is the slope gradient.

In conclusion, the topographic conditions are indirect factors and play roles on rill initiation through their effects on other factors. The ranges of the critical topographic values are not fixed and determined by the combination functions of other controlling factors on rill erosion, which should be further investigated.

4.3 Critical soil conditions

Many researchers used critical soil shear stress as an index to quantitatively describe the threshold soil conditions for rill initiation. Soil shear strength has been often used to predict shear stress though limiting and contradictory results are achieved (Léonard and Richard, 2004; Li *et al*., 2010). Soil critical shear stress determined by Yao *et al*. (2008) range from 1.33 Pa to 2.63 Pa, with an average of 1.94 Pa. Tang *et al*. (2004) found that the critical soil shear stress for rill initiation ranges from 1 Pa to 2 Pa with an average value of 1.31 Pa, by using the tracing method of rare earth element. Lei *et al*. (2008) presented a rational method for estimating critical shear stress and found that the critical shear stress (3.2–4.6 Pa) increases slightly with the increase of slope gradient (5°–25°). Léonard and Richard (2004) found that most time critical shear stress values are varied between 0 Pa and 10 Pa with two exceptions by Krishnamurthy (1983). In the jet experiment of Krishnamurthy, critical shear stresses range between 0 Pa and 35 Pa, while in his flume experiment, critical shear stresses range between 0 Pa and 1 Pa. Knapen *et al*. (2007) thought that critical shear stress values range between 0 Pa and 15 Pa (n = 522) based on soil and environmental properties reported in literature. Zhang *et al.* (2008) found that the critical shear stress was affected by land uses and ranged from 2.08 Pa to 6.30 Pa.

The critical shear stress is a significant parameter in empirical Water Erosion Prediction Project (WEPP) model, and mostly is calculated by using the soil parameters like texture, dry bulk density, and organic matter content. However, in some equations the so-called 'critical' shear stress consists of hydraulic parameters like water depth, water width or fluid density (Wirtz *et al*., 2013). Léonard and Richard (2004) estimated a linear relationship between runoff critical shear stress and soil shear strength:

$$\tau_c = \beta\sigma_s \tag{12}$$

where τ_c is critical shear stress; and σ_s is soil strength. The estimated value for β is 2.6 × 10^{-4} and its standard error is 1.2 × 10^{-5}.

Some researchers made efforts to find the relationships between critical soil shear stress and other controlling factors of rills. Lei and Nearing (2000) obtained a linear correlation between slope gradient and critical soil shear stress of rill initiation:

$$\tau_c = A + BS \tag{13}$$

where τ_c is the critical soil shear stress; and S is the slope gradient.

Collison and Simon (2001) found the critical shear stress for head cutting of rill initiation:

$$\tau = c' + (\sigma - \mu_a)\tan\phi' + (\mu_a - \mu_w)\tan\phi^b \tag{14}$$

where τ is the critical soil shear stress for head cutting of rill initiation (kPa); c' is the effective soil cohesion (kPa); σ is the positive soil stress (kPa); μ_a is the air pressure in the soil pore; μ_w is the water pressure in the soil pore, ϕ' is the effective of soil internal friction angle; ϕ^b is the increasing rate of soil shear stress with the increase of soil suction.

All these results are either obtained from laboratory experiments or theoretical calculations. Therefore, the obtained critical values for rill initiation are depended on certain experiment conditions or certain theoretical assumptions. The common agreements are: certain conditions are necessary for rill initiation and the critical conditions are not a fixed value but varied with the combinations of different factors. The critical values under complex combinations of different factors should be further investigated.

5 Conclusions and Recommendations

Intensive investigations have been conducted to explain the development processes of rill erosion and their influencing factors. Currently, it is agreed that runoff erosivity and soil erodibility have direct impacts on rill erosion process, while other factors may have indirect influences on rill erosion through increasing or decreasing the effect of the direct factors. Although great efforts have been made, due to the complexity and stochasticity of rills, there are many unclear fields, such as dynamic changes of rill networks, inherent mechanisms of controlling factors on rill erosion and their combination functions, the relationships between critical values for rill initiation and other factors. Recommendations on further investigations are given as follows.

(1) Dynamics of rill networks should be further concentrated. To avoid the limitations of the investigations on rill networks by deduction from theoretical models, it is necessary to further quantitatively describe the dynamic changes of rill network by using advanced digital photogrammetry technologies. In addition, it is of significance to identify the controlling factors on rill morphological development, to explain how these factors affect rill network evolution, and the responses of these controlling factors to the changing of rill networks. Understanding the mutual feedback between rill flows and rill morphological changes are forefront focuses of the prediction model on slope erosion.

(2) Physical mechanisms of different controlling factors should be further investigated. Further investigations should be conducted on the physical mechanisms of combined effects of different influencing factors, not just on the empirical relationships as examined in the past. It is necessary to quantitatively identify the contributions of different factors to rill erosion process. With the improvements of experimental technologies, the combined effects or interactions of multiple factors on rill erosion process should be further explored and better understood.

(3) Relationships of certain critical values with other related factors should be further understood. In the past, great efforts were made to find critical conditions for rill initiation. However, inconsistent results were obtained by different researchers under different experiments, which is mainly because the critical values are significantly influenced by other factors, and because the critical condition is not a fixed value but the combined effects of different factors. To better understand the critical conditions of rill initiation, further investigations should be conducted to explain the relationships of certain critical values with other related factors.

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