The Combined Effect of Wind and Rain on Interrill Erosion Processes

G. Erpul[1], D. Gabriels[2] and L.D. Norton[3]

[1]Faculty of Agriculture, Department of Soil Science, Ankara University, Diskapi, Ankara, Turkey
[2]Department of Soil Management and Soil Care, Ghent University, Ghent, Belgium
[3]USDA – ARS National Soil Erosion Research Laboratory, Purdue University, West Lafayette, USA

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[1] erpul@agri.ankara.edu.tr

Introduction

Wind-driven rain is described as raindrops falling through a wind field at an angle from vertical under the effects of both gravitational and drag forces. Wind-driven raindrops gain some degree of horizontal velocity and strike the soil surface with an angle deviated from vertical. Additionally, the distribution and intensity of rainfall on sloping surfaces differs depending on wind direction and velocity. Schematic representation of wind-driven rain incidental on a sloping soil surface is given in Figure 1.

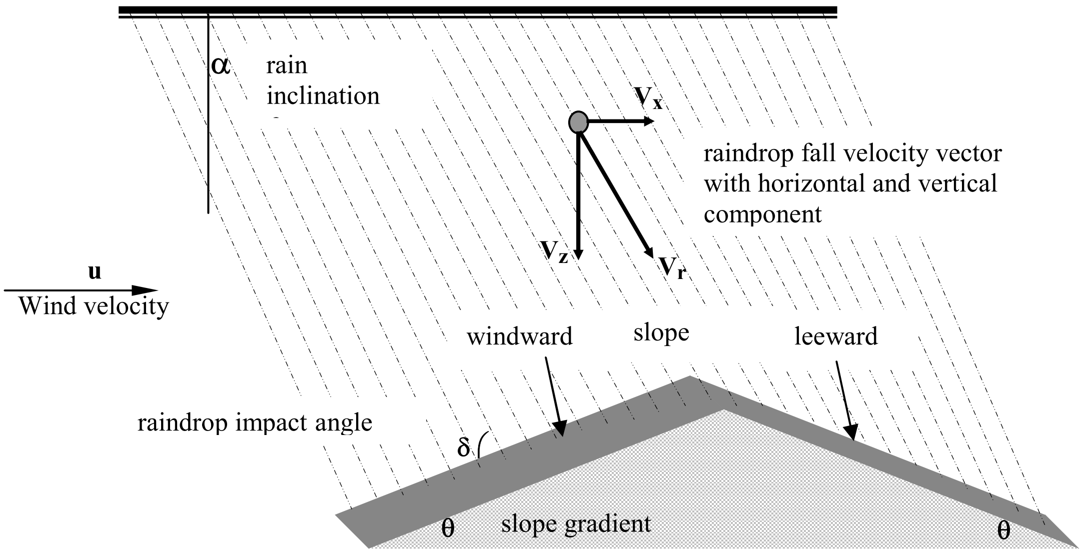

Figure 1. Schematic representation of wind-driven rain with an angle from vertical and incident on sloping surface.

The changes in raindrop trajectory and frequency with wind velocity and direction can have significant effects on rainsplash detachment process. The resultant impact velocity, impact angle, and impact frequency of raindrops determine the magnitude of rainsplash detachment by wind-driven rain. This differs from the detachment process by windless rain, in which a straight-line trajectory of raindrops and accordingly greatest rainfall intensity for a given rain are implicitly assumed. Wind, as well as slope and overland flow, is another possible factor capable of transporting detached particles by raindrop impact. Once soil particles are entrained in the splash droplets that have risen into the air by raindrop impact, wind velocity gradient will transport these particles. Obviously, in addition to its role in the rainsplash detachment process, the wind accompanying rain is an important consideration in the rainsplash transport process, which can cause a net transportation in wind direction. In wind-driven rains, wind velocity and direction is expected to affect not only rainsplash detachment and transport processes but also shallow flow sediment transport induced by raindrop impacts with an angle on flow and the rainsplash trajectories of soil particles within flow.

Under wind-driven rain, the interrill transport process is a combined work of both rainsplash sediment transport and raindrop-impacted shallow flow sediment transport. The rainsplash process acts alone until runoff occurs, and net soil transport is caused by wind. As soon as runoff starts, the flow-driven process begins to transport the detached soil particles. This is different from the approach of recent interrill erosion models that soil detached by the rainsplash will be subsequently transported by overland flow.

The Effect of Wind on Raindrop Impact and Rainsplash Detachment

Raindrop impact frequency

The raindrop fall trajectories influenced by the horizontal wind velocity and the geometry of the surface, slope gradient and aspect, leads to differences in the amounts of raindrops hitting the soil surface.

$$\phi = \frac{I_a}{I} = \cos(\alpha \mp \theta) \qquad [1]$$

where ϕ is the impact efficiency, I the rainfall intensity in respect to a plane normal to the rain vector, I_a the actual intensity, α the raindrop inclination from vertical, and θ the slope gradient. In the Eq. [1], the positive sign indicates the windward facing slope and the negative sign corresponds to the leeward facing slope, implying raindrop deficit with the same values of the slope gradient and the raindrop inclination. Eq. [1] points in fact to that the actual rate of wind-driven raindrop impact per unit area varies with the rain inclination induced by the horizontal wind velocity and the slope gradient and aspect (De Lima, 1990). Theoretically, in the situations where wind direction from which rain is falling z_α and the plane of surface on which raingauges are placed z_θ are on the same plane, rain interception will be the greatest in the windward slopes as α is approaching θ, and no raindrops will be intercepted by the surface as the sum of α and θ is approaching 90 degrees.

Angle of rain incidence

The mean angle of rain incidence between wind vector and the plane of the surface is calculated as a function of the rain inclination, slope gradient and aspect and given by the cosine law of spherical trigonometry (Sellers, 1965):

$$\cos(\alpha \mp \theta) = \cos\alpha \cos\theta \pm \sin\alpha \sin\theta \cos(z_\alpha \mp z_\theta) \qquad [2]$$

where z_α and z_θ are the azimuth from which rain is falling and the azimuth towards which the plane of surface is inclined, respectively. Since wind-driven raindrop strikes the soil surface with an angle deviated from the vertical because of its horizontal and vertical velocities, its vertical impact pressure differs from that of the vertically falling raindrop. No impact pressure acts on a soil surface by a raindrop with a velocity 'v' regardless of its magnitude that is parallel to the surface, and the soil surface experiences a maximum impact pressure when raindrop fall perpendicular to the soil surface (Ellison, 1947). In general, if a raindrop falls at an angle of incidence $(\alpha \mp \theta)$, only the component of velocity $v\cos(\alpha \mp \theta)$ normal to the surface gives rise to an impact pressure (Heymann, 1967; Springer, 1976).

Figure 2 shows calculated average rain inclination (a) from vertical and average angle of incidence (b) between the wind vector and the plane of surface as a function of horizontal wind velocity. These results were obtained in a wind tunnel rainfall simulator facility at Ghent University in Belgium (Gabriels et al., 1997) with the rains driven by wind velocities of 6, 10 and 14 m s^{-1} and incidental on both windward and leeward slopes of 7, 15 and 20% (Erpul et al., 2003a). Median drop sizes were 1.63, 1.53, and 1.55 mm for the rains driven by 6, 10 and 14 m s^{-1} winds, respectively.

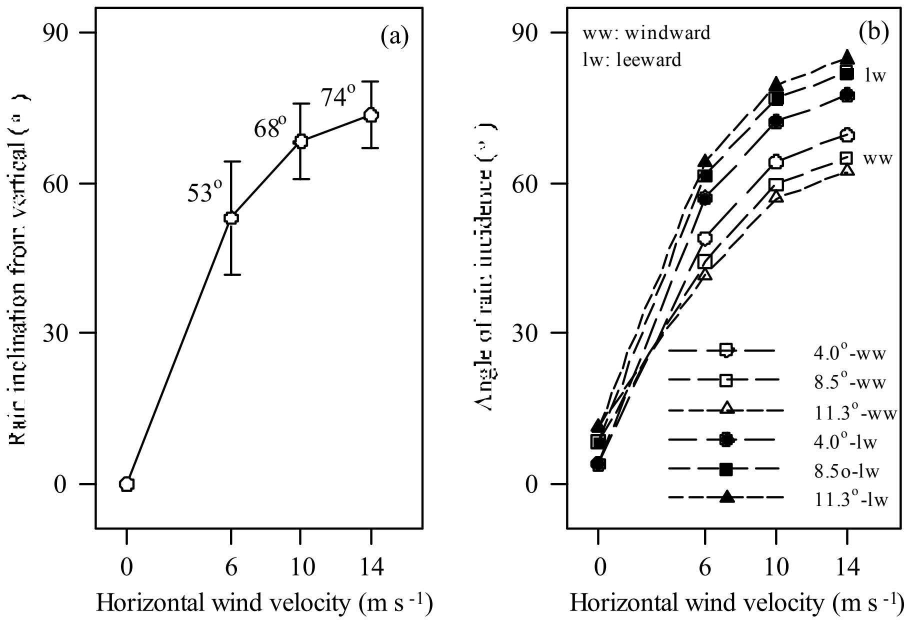

Figure 2. Calculated average rain inclination from vertical (a), and average angle of incidence between the wind vector and the plane of surface (b) as a function of horizontal wind velocity.

Raindrop impact velocity

For an understanding of dynamics of wind-driven raindrop, one needs to know the full spectrum of forces acting on the raindrops entering a wind field. For a two dimensional analytical model to estimate raindrop trajectories, the equations for vertical z and horizontal along wind x are as follows:

$$m\frac{\partial^2 z}{\partial t^2} = mg - \rho_a g\forall - \frac{1}{2}C_d\rho_a\left(\frac{\partial z}{\partial t}\right)^2 A \qquad [3]$$

$$m\frac{\partial^2 x}{\partial t^2} = -\frac{1}{2}C_d\rho_a\left(\frac{\partial x}{\partial t}\right)^2 A \qquad [4]$$

If raindrops are considered spherical of diameter d (m) and density ρ_w (kg m^{-3}), then the mass of the raindrop is $m = (\rho_w/6)\pi d^3$ (kg) with the projected frontal area of $A = \pi d^3/4$ (m^2), and the raindrop volume $\forall = \pi d^3/6$ (m^3); *g* is the gravitational acceleration (m s^{-2}); ρ_a is the air density (kg m^{-3}); C_d is the drag coefficient on the raindrop and calculated as a function of Reynolds number R_e:

$$R_e = \frac{\rho_a u d}{\mu} \qquad [5]$$

where u is free stream wind velocity (m s^{-1}) and μ the viscosity of air (N s m^{-2}). Eq. [3] and Eq. [4] show that the forces acting on the raindrop are due to gravity, buoyancy, and drag. It is here assumed that raindrops reach their terminal velocities in the z-direction and satisfy $m(\partial^2 z/\partial t^2) = 0$ and the x-component of the raindrop velocity is a function of horizontal wind velocity profile, $m(\partial^2 z/\partial t^2) = f(u_z)$. An expression for the horizontal raindrop velocity with respect to the fall height $[\partial V_x/\partial z]$ is derived using Eq. [3] and Eq. [4] (Pedersen and Hasholt, 1995):

$$\frac{\partial V_x}{\partial z} = \frac{3C_d\tilde{n}_a}{4d\tilde{n}_w}(V_x - u) \qquad [6]$$

Rainsplash detachment

When raindrops impact a soil surface, the pressure builds up at the raindrop-soil interface. Pressure acting on the contact area leads to a force normal to the soil surface and forces the splash droplets to escape laterally, entraining soil particles. Rainsplash detachment results from these splashes (Huang et al., 1982; Moss and Green, 1983). In the wind-driven rains, velocity, angle, and frequency of raindrop impact determine the magnitude of rainsplash detachment. If we assume that the effect of wind shear stress on the detachment is insignificant when compared to the effects of the impacting raindrops, the rainsplash detachment rate (D) at which soil particles are supplied into the air is a linear function of the raindrop kinetic energy (E_r) (Erpul et al., 2003a):

$$D = K(E_r) = K\left\{\frac{1}{2}m\left[V_r^2\cos^2(\alpha \mp \theta)\right]\right\} \quad [7]$$

where, K is the soil detachment factor, and $V_r^2 = V_z^2 + V_x^2$ with $V_z = \partial z/\partial t$ and $V_x = \partial x/\partial t$. Since raindrops with Ξ_a (#) strike a soil surface under wind-driven rain, the total kinetic energy flux E_{rn} (W m^{-2}) is described by $E_m = \hat{I}_a E_r = \hat{I} E_r \cos(\alpha \mp \theta)$, and Eq. [7] becomes:

$$D = K\Xi\left\{\frac{1}{2}m\left[V_r^2\cos^3(\alpha \mp \theta)\right]\right\} \quad [8]$$

The maximum soil detachment rate for the case of the rainsplash transport occurs when there is no water running on the soil surface. Therefore, considering the effect of shallow overland flow depth on the detachment, the contribution of impacts of wind-driven raindrops in interrill flow-driven sediment transport process can be given by:

$$D_\Phi = K\Xi\left\{\frac{1}{2}m\left[V_r^2\cos^3(\alpha \mp \theta)\right]\right\}\Phi \quad [9]$$

where, D_Φ is the soil detachment term for overland flow-driven transport, and Φ is the parameter introduced to distinguish the raindrop impact on a bare soil surface from the impact on a surface with a shallow water depth.

Sediment Transport from Interrill Areas under Wind-Driven Rain

Unlike recent erosion prediction technologies, a technology considering the combined effect of wind and rain on the erosion processes hypothesizes that when raindrops first impact bare soil, wind-driven rainsplash process operates alone, and by the time that runoff occurs, produces net transport and provides the first stage of transport sequence of interrill soil erosion. This reasoning implies that sediment transport by rain-impacted shallow flow shows a complementary relationship to the rainsplash, which rapidly becomes less effective as flow depth increases from zero. Therefore, total interrill erosion under wind-driven rain is defined by:

$$q_i = Q_s + q_s \quad [10]$$

where, q_i is the total interrill sediment transport, Q_s is the wind-driven rainsplash transport, and q_s is the sediment transport by raindrop-impacted shallow flow.

Wind-driven rainsplash transport

The approach to the rainsplash transport process under wind-driven rain is based on the concept that once lifted off by the raindrop impact, the soil particles entrained into the splash droplets travel some distance, which varies directly with the wind shear velocity (Erpul et al., 2002). The raindrop impacts induce the process that wind would otherwise be incapable of transporting wet and cohesive soil particles. Erpul et al. (2003b) adequately described the process by relating transport rate to the flux of rain energy (E_{rn}, W m^{-2}) and the wind shear velocity (u_*, m s^{-1}):

$$Q_s = K_1 E_{rn}^{a_1} u_*^{b_1} \qquad [11]$$

where K_1 is the relative soil transport parameter for the wind-driven rainsplash process, and a_1 and b_1 are the regression coefficients.

Sediment transport by raindrop impacted shallow flow

The essential processes of sediment transport by rain impacted thin flow are rainsplash detachment and flow-driven transport. In other words, shallow flow-driven sediment transport from the interrill areas is determined by the interaction of rain and flow parameters. Julien and Simons (1985) investigated the applicability of several sediment transport equations under different hydraulic conditions. The transport capacity of rain-impacted thin flow was characterized by rainfall intensity (I), unit discharge (q), and channel bottom slope (S) by:

$$q_s = K I^a q^b S^c \qquad [12]$$

where, q_s is the sediment transport rate by rain-impacted thin flow, and K, a, b, and c are the experimental coefficients. Under wind-driven rains, Erpul et al. (2003b) developed a simplified model equation similar to Eq. [12]. Flux of rain energy provided much better result than the intensity since it accounted for the variations in the velocity and angle of raindrop impacts as well as that in the frequency of raindrop impacts:

$$q_s = K_2 E_{rn}^{a2} q^{b_2} S^{c_2} \qquad [13]$$

where, q_s is in g m^{-1} min^{-1} and q is in m^2 min^{-1}, and S in mm^{-1}. K_2 is the relative soil transport parameter for shallow flow-driven process, and a_2, b_2, and c_2 are the regression coefficients.

Total sediment transport

Using Eq. [10], Erpul et al. (2003b) defined the total interrill erosion by:

$$q_i = K_1 E_{rn}^{a_1} u_*^{b} + K_2 E_{rn}^{a_2} q^{b_2} S^{c_2} \qquad [14]$$

The results of their study showed that, when compared to the contribution of the flow-driven transport, the contribution of the rainsplash transport was significant to the extent that it should not be neglected in accurately predicting water erosion from interrill areas under wind-driven rains (Figure 3).

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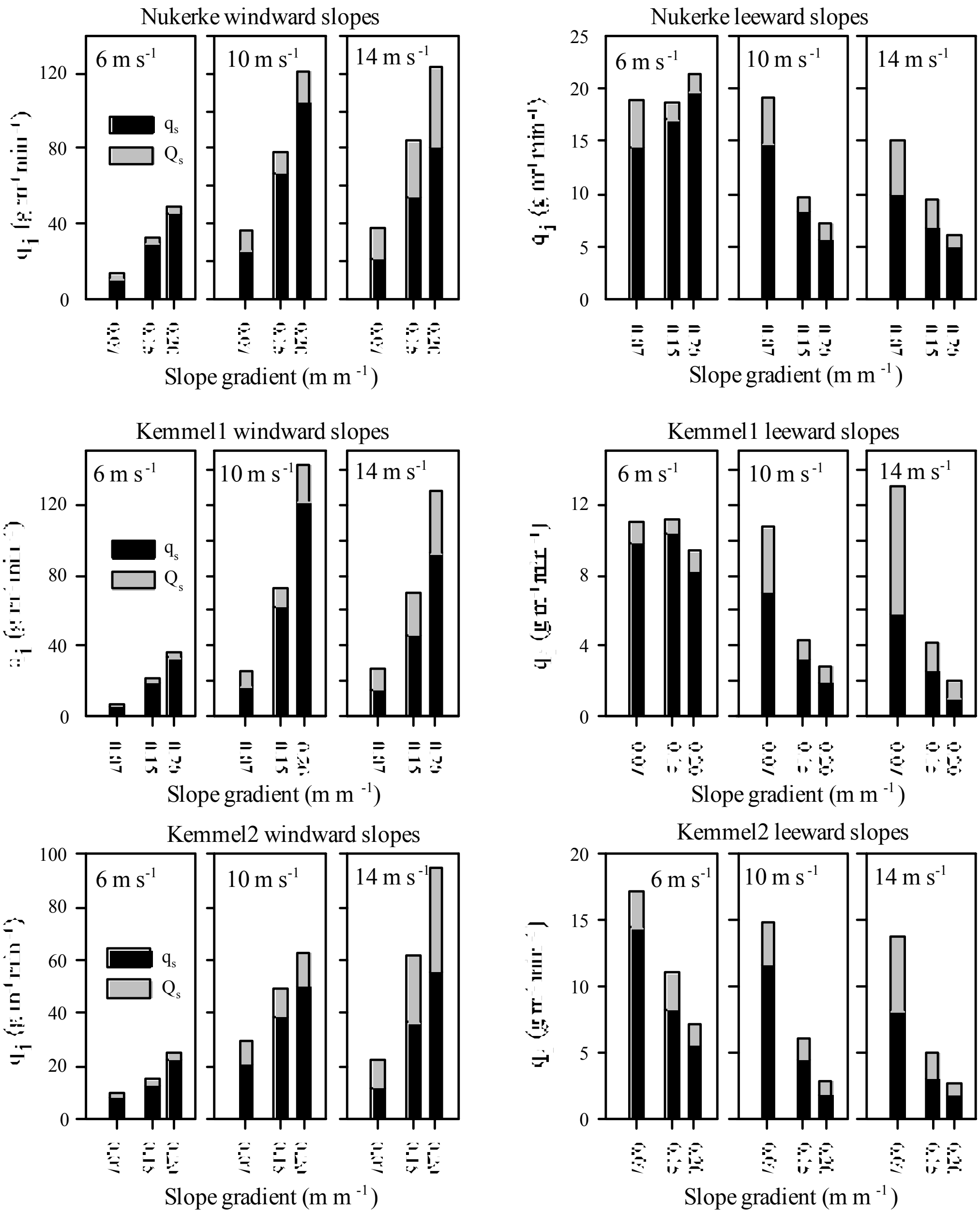

Figure 3. Total sediment transport from interrill areas based on the wind-driven rainsplash and the sediment transport by the rain-impacted shallow flow for three soils.