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Interrill and rill erodibility in the northern Andean Highlands

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Abstract

There is a lack of quantitative information describing the physical processes causing soil erosion in the Andean Highlands, especially those related to interrill and rill erodibility factors. To assess how susceptible are soils to erosion in this region, field measurements of interrill (Ki) and rill (Kr) erodibility factors were evaluated. These values were compared against two equations used by the Water Erosion Prediction Project (WEPP), and also compared against the Universal Soil Loss Equation (USLE) erodibility factor. Ki observed in situ ranged from 1.9 to 56×10^5 kg s m^{-4} whereas Kr ranged from 0.3 to 14×10^{-3} s m^{-1}. Sand, clay, silt, very fine sand and organic matter fractions were determined in order to apply WEPP and USLE procedures. Most of the evaluated soils had low erodibility values. However, the estimated USLE K values were in the low range of erodibility values. Stepwise multiple regression analyses were applied to ascertain the influence of the independent soil parameters on the Ki and Kr values. After this, we yield two empirical equations to estimate Ki and Kr under this Andean Highlands conditions. Ki was estimated using as predictors silt and very fine sand, while Kr used as predictors clay, very fine sand and organic matter content. Relationship among Ki, Kr and K are described for the Highland Andean soils.

Keywords: Interrill erodibility; Rill erodibility; Portable rainfall simulator; Andes; WEPP; USLE

1. Introduction

More than 10 million rural inhabitants reside in the Mountainous region of the major Andean countries where moderate and severe soil erosion occurs (Zimmerer, 1993) However, quantitative studies on soil erosion as well as the knowledge on water and erosion processes are scarce in the Andes (Stroosnijder, 1997) compared with other areas in the world, especially those related to soil erodibility (Víctora et al., 2001; Zehetner and Miller, 2006). Published erosion rates are around 48 Mg ha^{-1} year^{-1} in Colombia (Ashby, 1985); 0 to 836 Mg ha^{-1} year^{-1} in Ecuador (Harden, 1988); 10 to 70 Mg ha^{-1} year^{-1} in Peru (Low, 1967) and 114 to 173 Mg ha^{-1} year^{-1} in Bolivia (Zimmerer, 1991). Current studies try to give a better approximation of the estimated erosion rates, because time- and scale-dependent aspects of soil loss and sediment transfer make comprehensive measurements difficult.

Inbar and Llerena (2000) determined sediment yield quantitatively from abandoned terrace areas in Central Andes of Peru. However, no calculation of erodibility values has been done in these plot studies. Sánchez et al. (2002) made a comparative study of soil erosion in the Venezuelan Andes. Soil losses were quantified by using erosion plots in areas covered by four types of vegetation (apple trees, pasture, natural forest, and horticultural crop in rotation). The lowest soil loss rated was associated to the natural forest, with an average value of 0.43 mg ha^{-1} year^{-1} and the highest occurred with horticultural crops in rotation, with an average value of 15 Mg ha^{-1} year^{-1}. They calculated the soil erodibility factor (K) of the Universal Soil Loss Equation (USLE—Wischmeier and Smith, 1978) based on the relation between aggregation, textural class and organic matter

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content of the topsoil. The *K* factor values were 0.030, 0.045, 0.032 and 0.038 Mg ha^{-1}/MJ ha^{-1} mm h^{-1} for natural forest, horticultural crops, pastures and apple plantation treatments, respectively. Zehetner and Miller (2006) studied the erodibility and runoff-infiltration characteristics along an altitudinal Entisols–Inceptisols–Andisols sequence in the Andes of northern Ecuador. Using disturbed soil samples packed into small pans and placed on a 9% slope, simulated rainstorm with varying intensities was applied for a duration of 30 min. During the simulated event, runoff and eroded sediment were collected in 5-min intervals and measured by weight before and after drying. They calculated the interrill erodibility with the original WEPP interrill equation (Flanagan and Nearing, 1995). Ki ranged from 0.5 to 7.9×10^5 kg s m^{-4}.

Natural rainfall represents natural conditions at a given place; however, data acquisition is difficult due to the lack of control of the spatial and temporal distribution of rainfall intensity (Moore et al., 1983). A more cost-effective alternative is to use rainfall simulators to apply controlled rainstorms to small plots (Kamphorst, 1987; Esteves et al., 2000). Portable rainfall simulators used on small plots give sufficient flexibility to study a variety of processes (e.g. infiltration, irrigation, interrill erosion and water quality) on different soils and slopes and different land uses (Sharply et al., 1999; de Lima et al., 2002) and can be used to collect data in a relatively short period, providing maximum control over plot conditions and rainfall characteristics (Wilcox et al., 1986). Performing experiments with a rainfall simulator make possible to compare runoff rates and soil detachment by raindrop impact between sites at which the same experimental procedure was used, thus providing a basis from which to understand spatial patterns of vulnerability to soil erosion over a broad area. However, splash detachment rates from very small plots can exceed soil erosion rates determined in large, conventional plots for comparable natural rainstorms because conventional measure require entrained particles to be transported to the lower edge of the plot (Harden, 2001).

The main disadvantages of using rainfall simulators are related to scale. First, it is cheap and simple to use a small simulator which rains onto a test plot of only a few square meters, but simulators to cover field plots are large, expensive and cumbersome, and secondly, measurements of runoff and erosion from simulator tests on small plots cannot be extrapolated to field conditions. They are best restricted to comparisons, such as which of three cropping treatments suffers least erosion under the specific conditions of the simulator test, or the comparison of relative values of erodibility of different soil types (Hudson, 1993).

With the development of USLE (Wischmeier and Smith, 1978) — the identification of the soil erodibility *K* factor became a central issue in erosion studies (Bryan et al., 1989). USLE continues being applied all over the world and provides a practical alternative to estimate *K*. Different studies show different results of applying USLE in the tropics (Vanelslande et al., 1984; Mati et al., 2000; Mati and Veihe, 2001; Baumann et al., 2002; Kim et al., 2005; Weill et al., 2006; Millington, 2006). Problems with the use of USLE in this environment appeared to be: (1) rainfall intensities are higher than those occurring in eastern USA, where it was developed; (2) different methods of soil aggregation that are found in tropical soils — particularly bonding by iron, aluminium and organic acids; (3) farming occurring on more ecologically and topographically marginal areas; and (4) cropping and management factor which are radically different (Millington, 2006).

Erosion can be divided into two components: rill and interrill erosion. Interrill erosion is caused by soil particles being detached by raindrops and transported by overland flow. Rill erosion, however, is the detachment and transport of soil particles by concentrated flow: it is a function of the shear of the water flowing in the rill (Lal and Elliot, 1994). Computer simulation models like the Water Erosion Prediction Project – WEPP (Nearing et al., 1989) – developed by the United States Department of Agriculture (USDA) require the input of two erodibility values for each soil type: interrill (Ki) and rill (Kr) erodibility. If the inputs are not available, WEPP includes two regression equations to calculate Ki and Kr, also based on soil properties like content of clay, silt, very fine sand, sand and organic matter (Flanagan and Nearing, 1995). The main objective of this study is to determine the interrill and rill erodibility values for a northern Andean highland watershed in Peru and to compare field measurements with existing models that describe erodibility.

2. Material and methods

2.1. The study area

The Northern Andean Cordillera in the district of La Encañada belongs to a transition zone between an inter-Andean valley and a highland plateau. It is a 160 km^2 watershed located between 7°0′21″S and 7°8′2″S latitude and 78°11′22″W and 78°21′31″W longitude. The altitude ranges from 2950 to 4100 meters above the sea level. As a part of the Andean relief, this watershed presents a variety of geomorphic characteristics, resulting in a complex topography. Seventy four percent of the area presents from moderate to strongly steep hillsides, containing sedimentary deposits

Table 1
General climatic conditions (1995–2000) in La Encañada watershed

Weather stations (m a.s.l.)	Solar radiation (MJ m^{-2} day^{-1})	Maximum temperature (°C)	Minimum temperature (°C)	Rainfall (mm)	Number of days with rainfall
La Toma (3590)	19.9	10.8	2.8	832	193
Usnio (3260)	19.2	14.2	6.1	720	152
Manzanas (3020)	18.3	16.2	5.9	633	177
Average	19.1	13.7	4.9	767	174

from the Cretaceous like sandstones, limestones and shales. The remaining area are characterized by hills and by the high lying but gently sloping valley with an alluvial floodplain at the bottom of the watershed (Baigorria et al., 2002), formed by more recent deposits (Quaternary).

The main meteorological information is presented in Table 1, from three weather stations within the watershed. The rainfall amount per year is variable, ranging from approximately 300 mm (for a Neutral year) to 1250 mm (for an El Niño or La Niña years) (Romero, 2005). Maximum

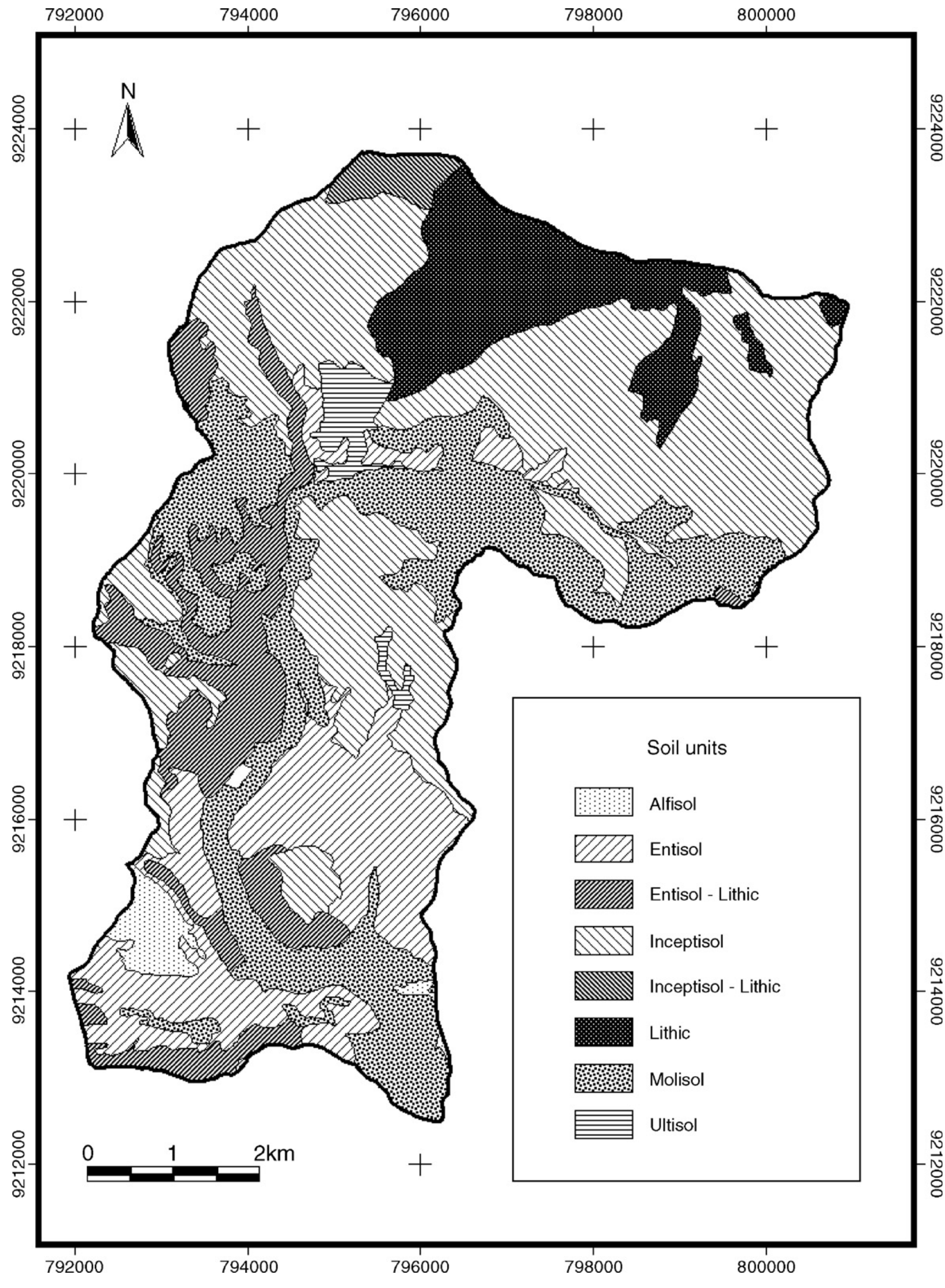

Fig. 1. Soil map of La Encañada watershed, Peru.

Table 2
Maximum and minimum physical soil properties at 21 points where Ki was measured in La Encañada watershed

	Clay (%)	Silt (%)	Sand (%)	Very fine sand (%)	Organic matter (%)
Minimum	2	16	22	4	2.3
Maximum	36	44	78	27	7.2

rainfall intensities as high as 150 mm h^{-1} has been registered, those events representing only 5% of the total events in the area, but they can be the main cause of the erosion process in the area. However, most of the rainfall events do not exceed 7.5 mm h^{-1} of rainfall intensity (Romero, 2005). Additional information of the climate around the northern Andean highlands and of the study area can be found at Baigorria et al. (2004) and Baigorria (2005).

The soil parent material consists principally of limestone, sandstone, siltstone and shale. There are also unconsolidated soil parent materials like alluvium and fine and coarse fluvio-glacial, glacial, alluvio-colluvial or colluvial materials. The dominant soils in the area are classified as Entisols (Fluvents), Inceptisols (Ochrepts and Umbrepts) and Mollisols (Aquolls and Ustolls) in the U.S. Taxonomic Classification System (INRENA, 1998) being the most common soil texture the sandy loam (Fig. 1). The organic matter content in these soils is medium to high (over 2%).

Deep soils with high organic matter content are cultivated, with the most important crops being cereals, potato, maize and legumes. Crop yields are variable, depending on soil fertility and on climatic conditions. Low fertile shallow soils which display soil erosion characteristics are sometimes cropped, even when they occur on steep slopes. However, most of them are only suitable for natural pasture (Proyecto PIDAE, 1995; Romero, 2005). Approximately 65% of the area has a slope gradient less than 15%. The remaining 35% can reach up to 70%.

2.2. Interrill erodibility determination

Erodibility has generally been deduced from rainfall simulations experiments on soil samples (Barthès and Roose, 2002) since this evaluation in the field is often expensive or time-consuming. Imeson and Vis (1982), Barthès and Roose (2002) and Kunwar et al. (2003) pointed out the importance of aggregate stability as an important property related to soil erodibility and water acceptance. However, for the purpose of our study, we used a rainfall simulator.

Interrill detachment was measured using a portable rainfall simulator (Kamphorst, 1987). With this simulator one measures the runoff, soil loss and infiltration generated by a standardized rain shower on a plot with a standard slope and surface area. It is also designed for erodibility studies (Kamphorst, 1987). The runoff plot of the rainfall simulator covers an area of 0.0625 m^2 and is surrounded with a metal frame so that all runoff water is collected at the lowest point. The rainfall intensity produced by the rainfall simulator was about 360 mm h^{-1}. The highest intensity found in the study area was 150 mm h^{-1}. This intensity is needed to compensate for the short falling distance, in order to obtain a realistic kinetic energy of the raindrops. Though the practical use of the absolute values of these measurements is disputable, the results are useful for comparing the erosion rates of different sizes (Posthumus, 2005).

Twenty one points were selected within the watershed. Table 2 shows the minimum and maximum values of the main physical properties. Before the simulator was set up, stones and loose organic materials were carefully removed from each plot, taking care not to disturb the soil surface. After the simulator had been set up, a standard rain was applied for 5 min. A simulation was executed until a constant runoff rate was reached. As a consequence, most simulations took about 15 to 30 min. Runoff was sampled every minute after runoff was constant. Sediment that splashed off the front of the tray was collected; only down-slope splash erosion was measured but we assumed minimum side-splash erosion because the slope of the test plots was 20%. Runoff samples were oven-dried at 105 °C to obtain soil loss expressed in kg m^{-2}. Only bare-soil conditions were tested.

The observed interrill erodibility (Ki) values were calculated using the formula (Elliot et al., 1989):

$$D_i = \mathrm{Ki} I^2\ S_f, \qquad (1)$$

where D_i = interrill erosion rate (kg m^{-2} s^{-1}); Ki = interrill erodibility (kg s m^{-4}); I = rainfall intensity (m s^{-1}) and S_f = slope factor (dimensionless = $1.05-0.85\exp^{(-0.85\ \sin[\theta])}$ where theta is expressed in degrees).

At each of the sites Ki was also estimated using the formula used by the WEPP model (Flanagan and Nearing, 1995):

$$\mathrm{Ki} = 2,728,000 + 19,210,000\ \mathrm{vfs}, \qquad (2)$$

where vfs = very fine sand fraction.

2.3. Rill erodibility determination

Rill erodibility (Kr) was measured using a procedure recommended by Lal and Elliot (1994). Seventeen sites were chosen within the watershed. These sites, which did not necessarily overlap with those used for the Ki determination, were located where tap water was available. It was attempted to cover most soil types. Table 3 shows the minimum and maximum values of the main physical properties of the soil at these sites.

Using a shovel, artificial rills 0.1 m wide and 3 m, 6 m, and 9 m long were created up and down the slope. Approximately 10 min of artificial rain was applied on each rill using a

Table 3
Maximum and minimum physical soil properties at 17 points where Kr was measured in La Encañada watershed

	Clay (%)	Silt (%)	Sand (%)	Very fine sand (%)	Organic matter (%)
Minimum	5	20	20	3.5	0.6
Maximum	48	52	72	21.9	10.6

Table 4
Coefficient of determination (r^2), standard deviation and level of significance between interrill (Ki) and rill (Kr) erodibility and soil parameters, according to the multistep regression analyses

Soil parameters	Ki			Kr		
	S.D.	r^2	Level of significance	S.D.	r^2	Level of significance
Clay	1,281,498	0.024	ns	0.00389	0.078	ns
Sand	1,271,814	0.039	ns	0.00399	0.030	ns
Silt	1,279,035	0.028	ns	0.00404	0.04	ns
Very fine sand (VFS)	865,131	0.56	**	0.00388	0.083	ns
Organic matter	1,289,053	0.013	ns	0.00366	0.182	ns
Clay+Sand	1,306,278	0.039	ns	0.00400	0.086	ns
Clay+Silt	1,306,278	0.039	ns	0.00400	0.086	ns
Clay+VFS	888,549	0.556	**	0.00381	0.171	ns
Clay+OM	1,315,838	0.025	ns	0.00379	0.183	ns
Sand+Silt	1,306,278	0.039	ns	0.00400	0.086	ns
Sand+VFS	881,303	0.563	**	0.00371	0.217	ns
Sand+OM	1,305,259	0.041	ns	0.00357	0.275	ns
Silt+VFS	870,534	0.573	**	0.00386	0.149	ns
Silt+OM	1,311,101	0.032	ns	0.00353	0.289	ns
VFS+OM	886,857	0.557	**	0.00316	0.432	*
Clay+Sand+Silt	1,306,278	0.039	ns	0.00400	0.086	ns
Clay+Sand+VFS	894,978	0.574	**	0.00383	0.224	ns
Clay+Sand+OM	134,308	0.041	ns	0.00359	0.316	ns
Clay+Silt+VFS	894,978	0.574	**	0.00383	0.224	ns
Clay+Silt+OM	1,343,081	0.041	ns	0.00359	0.316	ns
Clay+VFS+OM	902,574	0.567	**	0.00317	0.469	*
Sand+Silt+VFS	894,978	0.574	**	0.00383	0.224	ns
Sand+Silt+OM	1,343,081	0.041	ns	0.00359	0.316	ns
Silt+VFS+OM	887,758	0.581	**	0.00327	0.435	ns
Clay+Sand+Silt+VFS	894,978	0.574	**	0.00383	0.224	ns
Clay+Sand+Silt+OM	1,343,081	0.041	ns	0.00359	0.316	ns
Sand+Silt+VFS+OM	908,719	0.587	**	0.00329	0.469	ns
Clay+Sand+Silt+VFS+OM	908,719	0.587	**	0.00329	0.469	ns

*,**, ns: significant at the 0.05, and 0.01 probability levels and non-significant, respectively.
VFS=very fine sand, OM=organic matter.

hosepipe, until an equilibrium outflow from the rill was observed. Then, while continuing the rain, tap water was added at the top of the plot, at 8, 10, 12 and 14 l min^{-1}. After reaching equilibrium outflow, the flow velocity and the concentration of sediment in the outflow were measured. For each combination of rill length and inflow sampling was done five times. The cross-sectional area (*A*) and wetted perimeter (*P*) were measured to determine the hydraulic radius (*r*) in each rill ($r=A/P$). Between each test, the rill was kept humid.

Using these measured data, the following rill detachment equation was applied to calculate Kr values (Elliot et al., 1989):

$$D_c = \mathrm{Kr}(\tau - \tau_c), \tag{3}$$

where D_c=rill detachment capacity for clean water (kg m^{-2} s^{-1}); Kr=rill erodibility (s m^{-1}); τ_c=critical shear stress (Pa); τ=hydraulic shear stress of flowing water (Pa; $\tau=\gamma rs$, where γ=specific weight of water=9810 N m^{-3}; r=hydraulic radius of rill, m; and s=hydraulic gradient of rill flow).

Measured rill detachment values (kg m^{-2} s^{-1}) were plotted against the hydraulic shear (Pa) values. The slope of the regression line is Kr, and the intercept with the horizontal axis is the critical shear, τ_c. Note that for each Kr value there were 60 data points plotted (5 samples * 3 rill lengths * 4 inflows).

At each of the 17 points Kr and τ_c were also estimated with the formulas used by the WEPP model (Flanagan and Nearing, 1995):

$$\mathrm{Kr} = 0.00197 + 0.030\ \mathrm{vfs} + 0.03863\mathrm{e}^{-184\mathrm{orgmat}} \quad \text{and} \tag{4}$$

$$\tau_c = 2.65 + 6.5\ \mathrm{clay} - 5.8\ \mathrm{vfs} \tag{5}$$

where vfs=very fine sand fraction and orgmat=organic matter fraction and clay=clay fraction.

At each point where interrill and rill erodibility were measured, soil samples were taken from the top 30 cm of the soil. The percentages of sand, silt and clay were determined in the laboratory, by the hydrometer method (Day, 1965). Very fine sand was determined by wet sieving. Soil organic matter was determined by the chromic acid digestion method (Walkley and Black, 1947). Permeability and structure classes were qualitatively determined in the field. Soil erodibility according to Wischmeier (*K*) values was determined using the Wischmeier's nomograph (Wischmeier and Smith, 1978).[1]

[1] *K* values are in US customary units [tons/(ac (hundreds of ft tons in)/(ac hr))]. Metric units for *K* in the SI system are [(t h)/(MJ mm)]. Divide *K* in US units by 7.62 to get *K* in SI units.

Table 5
Equation to estimate interrill erodibility (Ki) proposed by Flanagan and Nearing (1995) and newly proposed equation for determining Ki for Andean soils

Ki WEPP equation	Ki = 2,728,000 + 19,210,000 vfs
Proposed equation	Ki = −756,916 + 1,801,775 silt + 15,852,646 vfs
	s = 870,534; r^2 = 0.573

vfs: fraction of very fine sand; silt : fraction of silt.

A stepwise analysis was applied to determine the influence of the independent variables (sand, silt, clay, very fine sand and organic matter) on the dependent variables, Ki and Kr. Suitable regression equations were chosen according to the lower standard deviation, the higher correlation index and the less number of independent variables (see Tables 4, 5 and 6).

To visualise and determine the Ki–*K* and Kr–*K* relationships, the measured Ki and Kr values were plotted against their corresponding *K* values.

3. Results and discussion

Measured Ki values ranged from 1.9 to 56×10^5 kg s m^{-4} that differed from the estimated Ki using Eq. (2), ranged from 20 to 110×10^5 kg s m^{-4}. Measured Ki values are comparable to those reported by Zehetner and Miller (2006) where data ranges from 0.5 to 25×10^5 kg s m^{-4} for diverse Andean soils. As shown in Fig. 2, estimated values are higher than the observed ones. The distribution of the observed Ki values is shown in Fig. 3. The maximum Ki value (56×10^5 kg s m^{-4}) was measured in a soil with the largest very fine sand content (27%) and one of the largest contents of silt (42%). This maximum value coincided with the highest value predicted by Eq. (2) (80×10^5 kg s m^{-4}). The minimum Ki value (1.9×10^5 kg s m^{-4}) was observed in a soil with the lowest content of very fine sand (4%) although the soil had a sandy texture (70%) and contained a smaller amount of silt (12%). The lowest observed Ki value also coincided with the lowest value predicted using Eq. (2) (35×10^5 kg s m^{-4}). As expected, soils with high percentages of very fine sand and silt were the most erodible (Lal and Elliot, 1994).

Stepwise multiple regression analysis showed that the highest coefficient of determination was found between Ki and the very fine sand fraction (r^2=0.56). To other soil parameters like clay, silt, sand and organic matter, r^2 was statistically non-significant (r^2<0.04). The r^2 values for the combination of soil parameters are also shown (Table 4).

Table 6
Equation to estimate rill erodibility, proposed by Flanagan and Nearing (1995) and newly proposed equation for determining Kr for Andean soils

Kr WEPP equation	Kr = 0.00197 + 0.03 vfs + 0.03863e$^{-184\text{orgmat}}$
Proposed equation	Kr = −0.00778 + 0.00840 clay + 0.0341 vfs + 0.139 org mat
	s = 0.003168; r^2 = 0.469

vfs = fraction of very fine sand; orgmat = fraction of organic matter; clay = fraction of clay.

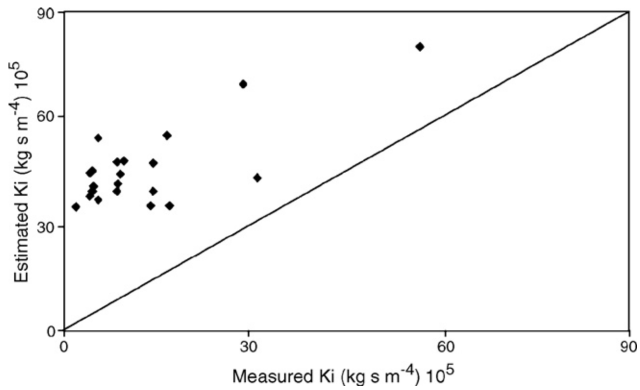

Fig. 2. Observed vs. estimated by WEPP equation values of interill erodibility (Ki) for soils in La Encañada watershed.

The observed Kr values ranged from 0.3 to 19×10^{-3} s m^{-1} (Fig. 4). Most of the studied soils has values from 0.5 to 2×10^{-3} s m^{-1} (Fig. 5). Kr estimations using Eq. (3) ranged from 2 to 45×10^{-3} s m^{-1}. Unfortunately, there are no rill erodibility data available in the literature that would allow for direct comparison of the studied with other Andean soils. The observed values showed that soils are resistant to detachment by concentrated flow. The minimum Kr value was observed in a soil with high clay content (36%), whereas the maximum Kr value was observed in a soil with high sand content (70%) and low clay content (10%). The cohesiveness of clay particles makes soils more resistant to detachment by water flow. Conversely, sand grains can easily be detached due to the lack of cohesion between them.

Stepwise multiple regression analysis showed low r^2 values between Kr and the individual soil parameters. However, when two or more soil parameters were considered together, the correlations improved, especially for very fine sand, organic matter and clay fractions (Table 4). The r^2 values, however, were lower than 0.5.

Observed τ_c values ranged from 0.64 to 19.96 Pa while values estimated by Eq. (5) varied between 2.1 and 4.9 Pa. The regression analysis showed non-significant differences and very low values of r^2 (<0.22) between τ_c and soil characteristics.

The USLE *K* erodibility factor was also estimated using the Wischmeier nomograph for all the locations where both

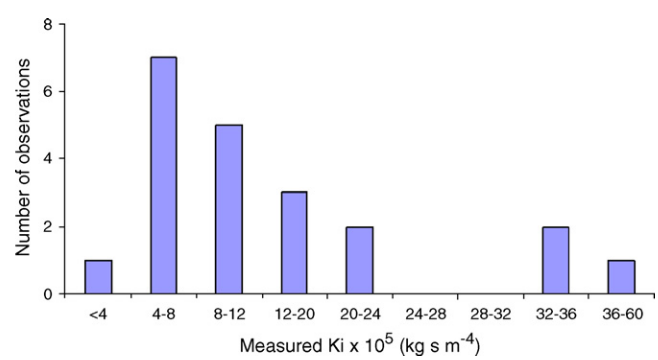

Fig. 3. Distribution of the observed Ki values Ki in La Encañada watershed.

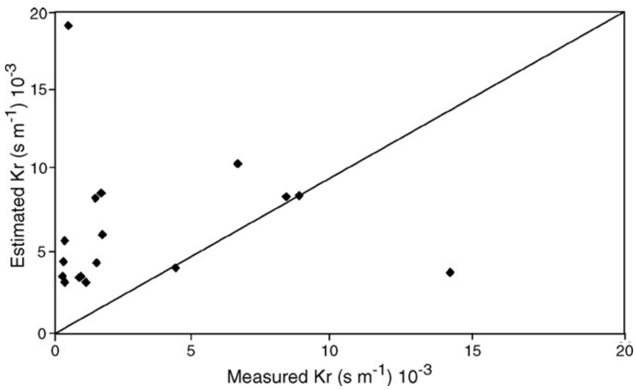

Fig. 4. Observed vs. estimated by WEPP equation values of rill erodibility Kr for soils in La Encañada watershed.

interrill and rill erosion were measured. For those soils containing more than 4% of organic matter, this value was fixed as maximum since the Wischmeier nomograph does not show organic matter values higher than 4% (Fig. 6). Most plots showed *K* values lower than 0.4. The nomograph gives a range from 0 to 0.7. According to these results, most of the evaluated soils are poorly erodible, which is in accordance with the observed values measured for both Ki and Kr. The highest estimated *K* value was for a soil with a high content of silt and very fine sand and a low content of organic matter.

Wischmeier's approach is an empirical approach to estimate soil erodibility, especially easily applied in areas where few data are available. Other works describe the applicability of this nomograph (El-Swaify and Dangler, 1977; Víctora et al., 2001; Baumann et al., 2002; Kidanu, 2004). However, there are other factors that greatly influence the soil erodibility values during an experimental test in the field, like previous cropping activities and/or soil management or the type of bonding that aggregate the soil particles and organic matter (Millington, 2006). Some variability can be found in those values compared to the most stable USLE soil erodibility *K*-values (Meyer and Harmon, 1984).

Tables 5 and 6 show WEPP equations for estimating Ki and Kr and the new proposed equations. The new equations were chosen according to the lowest standard deviation, the highest coefficient of determination (r^2) and the least number of variables (see Table 4), although these do not show very good correlations. Flanagan and Nearing's equations (Eqs. (2) and (4)), were designed for estimating the erodibility parameters in cropland soils containing more than 30% sand. These equations were used because most experiments had been carried out on such soils. We have not proposed an equation for the critical shear stress because it seems that the clay, sand, silt, very fine sand and organic matter fractions are not enough to explain τ_c.

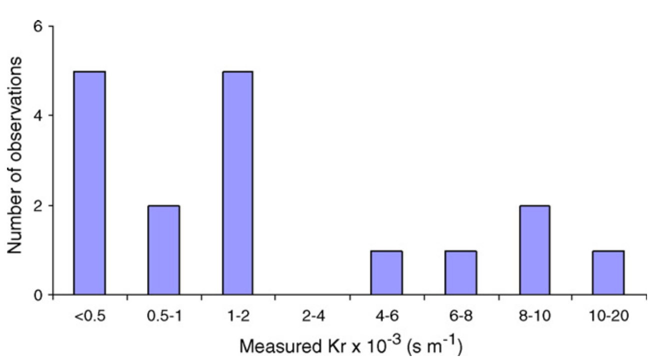

Fig. 5. Distribution of observed Kr erodibility values in Andean soils.

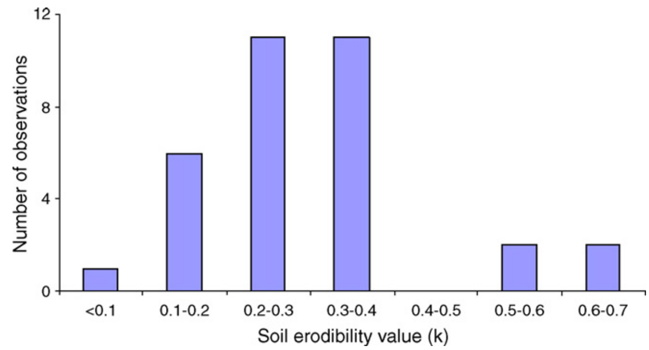

Fig. 6. Distribution of Wischmeier's *K* erodibility values in Andean soils.

In our study area, silt and very fine sands had a better r^2 with observed Ki values (Table 4). Our proposed equation explains about 57% of the interrill erosion process. Clay, very fine sands and organic matter had the best r^2 value for all the possible combination of soil parameters to determine Kr values and our proposed equation explains about 47% of the rill erosion processes. Clearly, our first attempt to estimate soil erodibility still needs to be improved: further investigation must be done to get a higher coefficient of determination between Ki and Kr and soil parameters.

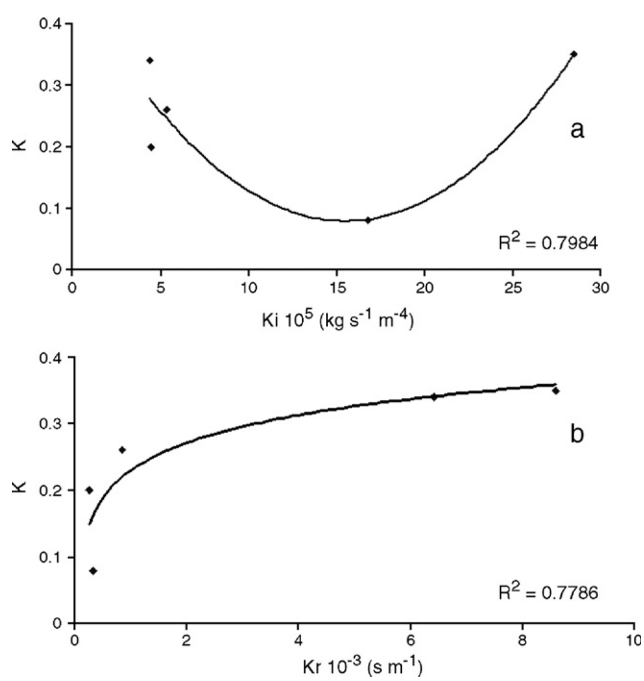

Fig. 7. Relationship between measured erodibility and Wischmeier's *K* for interrill erodibility (a) and rill erodibility (b).

Despite all the measurements we obtained in the watershed, Ki and Kr measurements coincided at only 5 points. Using these points we were able to establish a relationship between Ki, Kr and *K*. Fig. 7a shows a polynomial relationship between Ki and *K*. The highest values of *K* relates to lowest and to the highest values of observed Ki. The three points at the left of the graph represents soils with medium to high clay content and with a medium percentage of silt. Clay gives cohesiveness to soils, and therefore this characteristic was an important cause of the reduced Ki erodibility. Wischmeier's nomograph assumes that a soil becomes less erodible as the silt fraction decreases, regardless of the corresponding increase in the sand fraction or the clay fraction (Wischmeier and Smith, 1978). However, the erodibility of soils is a function of complex interactions between physical and chemical properties and can vary within a standard texture. It seems to be an oversimplification that erodibility can be related to a few physical properties only (Bryan et al., 1989).

Fig. 7b shows the relationship between Kr and *K* and corresponds to a logarithmic relationship. Though non-linear, this relationship is more in line with expectations.

4. Conclusions

Measured interrill (Ki) and rill (Kr) erodibility values were low in the evaluated Andean watershed. The most erodible soils were those with the greatest amount of silt and very fine sands and the most resistant were clayey soils. Silt and very fine sand were strongly correlated with the interrill erodibility values, whereas clay, very fine sand and organic matter were strongly correlated with rill erodibility. Two equations using these predictors were proposed. Ki values followed similar patterns and they are in agreement with other few results reported in the literature for the Andes; unfortunately, there are no rill erodibility data available that would allow for direct comparison of the studied with other Andean soils.

The USLE *K* factor using the nomograph approached fairly well to part of the obtained results, despite being in a high altitude tropical land. There is no direct relationship between Ki, Kr and *K*.

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