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Review

Soil erodibility for water erosion: A perspective and Chinese experiences

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ABSTRACT

Knowledge of soil erodibility is an essential requirement for erosion prediction, conservation planning, and the assessment of sediment related environmental effects of watershed agricultural practices. This paper reviews the status of soil erodibility evaluations and determinations based on 80 years of upland area erosion research mainly in China and the USA. The review synthesizes the general research progress made by discussing the basic concepts of erodibility and its evaluation, determination, and prediction as well as knowledge of its spatio-temporal variations. The authors found that soil erodibility is often inappropriately or inaccurately applied in describing soil loss caused by different soil erosion component processes and mechanisms. Soil erodibility indicators were related to intrinsic soil properties and exogenic erosional forces, measurements, and calculations. The present review describes major needs including: (1) improved definition of erodibility, (2) modified erodibility determinations in erosion models, especially for specific geographical locations and in the context of different erosion sub-processes, (3) advanced methodologies for quantifying erodibilities of different soil erosion sub-processes, and (4) a better understanding of the mechanism that causes temporal variations in soil erodibility. The review also provides a more rational basis for future research on soil erodibility and supports predictive modeling of soil erosion processes and the development of improved conservation practices.

1. Introduction

Soil erosion is a serious environmental, economic, and social problem. It not only causes severe land degradation and soil productivity loss, but also threatens the stability and health of society in general and sustainable development of rural areas in particular (Lal, 1991; Tang, 2004; Zheng et al., 2004; Jing et al., 2005). Estimating soil erosion rates and amounts began in the USA during the 1920s (Meyer and Harmon, 1984; Meyer and Moldenhauer, 1985), and rapidly advanced in the 1930s following the devastating impact of the "Dust Bowl" on the American Great Plains (National Climatic Data Center, 2009; Römkens, 2010). Since then, soil erosion research received increasing emphasis, and erodibility became an important parameter for estimating soil loss and implementing soil conservation practices. In recent years, soil erodibility has also become an imperative parameter for assessing and predicting environmental impacts on surface water bodies.

In erodibility studies and the development of erosion models, numerous publications on the effect of soil properties in erosion processes have assisted in better quantifying and defining soil erodibility (Römkens, 1985; Morgan et al., 1987; Bryan et al., 1989; Lal, 1991; Bryan, 2000). However, many factors and properties influence soil erodibility. Due to the complexity of erosion processes, the inherent complicated nature of soil erodibility, and the inadequate or incomplete data sets of many past studies, large gaps exist between what is available and what is needed in current soil loss prediction and soil conservation technologies. This is especially true when considering areas with various topographies, soil types, cropping practices and systems, and erosion patterns. Therefore, it is useful to discuss and update the concept of soil erodibility and its evaluation. In particular, it is worthwhile to review Chinese studies in soil erodibility research, which are not well-known internationally, and to compare them with studies in the western world.

This paper synthesizes available information concerning the concept of soil erodibility and erodibility factors, especially those related to China. The objectives of this paper are: (1) to review the development of the soil erodibility concept and discuss the concepts of anti-erodibility and anti-scourability, which were commonly used in China between the 1950s and the 1990s; (2) to discuss the evaluation of soil erodibility parameters in terms of intrinsic soil properties and exogenic erosional forces; (3) to investigate soil erodibility evaluation methods for different regions and describe their limitations; (4) to identify the spatio-temporal variability in soil erodibility; and (5) to highlight the challenges in current soil erodibility research. The review will provide a more rational basis for further research on soil erodibility and supports the predictive modeling of soil erosion processes by water.

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2. Soil erodibility concept

Soil erodibility is usually regarded as the susceptibility of a soil to erode. In a fundamental sense it should be defined as the amount of soil loss per unit exogenic force or erosivity such as rainfall, surface flow, and seepage. However, the term is often used more loosely (Dusan, 1982; Bryan et al., 1989). In addition, when this term has used, little distinction is made between the different modes of soil erosion under various surface and hydrological conditions, and cropping systems where a mix of different exogenic forces may operate together. Such exogenic forces also vary in time and space, and soil surface structures and properties change even during a storm event. As a result, soil erodibility has become a convoluted term. Plot studies on soil erosion are usually performed under highly controlled conditions based on an experimental design. Nevertheless, soil characteristics including the erodibility may also vary with the soil surface change during the process of an experiment.

Erosivity is the power of a storm to erode soil. It is usually determined from the storm characteristics such as rainfall intensity and energy. At the plot surface the storm power is expended in several components: (1) rainfall power, the product of the total amount of incident rainfall energy and intensity; (2) the runoff power or stream power, the product of the flow rate and the flow gradient; and (3) seepage power, the product of the seepage gradient and seepage flow rate. However, the seepage power is currently less considered in research on the erodibility. As known, seepage commonly occurs at down-slope areas or in places where soils are shallow or where topsoil is melted and subsurface soil is still frozen.

In China, erodibility was for some time (1950s–1990s) not a generally accepted term. Instead, Chinese researchers often used the terms anti-erodibility and anti-scourability (Zhu, 1954, 1960; Tian and Huang, 1960; Tang, 1961, 1964; Jiang, 1978; Huang, 1981; Li and Liu, 1987; Li and Zhu, 1990; Zhou and Wu, 1993; Wang et al., 1994; Jiang et al., 1995a; Liu and Liang, 1997; Zhao and Shi, 2003). Anti-erodibility refers to the soil's resistance to dispersion and suspension in disturbance water or under raindrop impact; while anti-scourability refers to the soil's ability to resist detachment by flowing water (Zhu, 1960; Jiang and Zhu, 1962; Wang et al., 1994; Liu, 1997). Although these terms involve the same basic soil properties as those used in the West, Chinese researchers emphasized resistance against erosion rather than factors facilitating erosion. The concepts of anti-erodibility and anti-scourability significantly contributed to soil erosion research in China (Liu et al., 1999). Anti-erodibility and anti scourability have often been evaluated under controlled experimental conditions (Liu et al., 1999; Jing et al., 2005), in which various soil erosion processes and sub-processes operate simultaneously (Tang, 1964, 2004; Bryan et al., 1989; Bryan, 2000; Morgan, 2005). Unfortunately, these concepts cannot readily be evaluated individually in the field (Liu et al., 1999; Zhang et al., 2001a).

3. Soil erodibility indicators (Qualitative evaluation stage)

As discussed, soil erodibility is not a simple concept and cannot readily be defined or calculated (Bryan et al., 1989; Gao et al., 1998; Bryan, 2000). Nevertheless, many attempts have been made to evaluate it. From a practical standpoint, soil erodibility may be discussed from relationships with intrinsic soil properties and exogenic erosive forces (Table 1).

3.1. Indicators related to intrinsic soil properties

Since the 1930s, most studies have expressed soil erodibility in terms of intrinsic soil properties. Initially, these studies concentrated on the role of soil texture, selected chemical properties such as soil organic matter, and soil profile descriptors such as structure and permeability. Bennett (1926) found a significant correlation between soil loss and the sesquioxide ratio indicating that the latter could be used as a predictor of soil erodibility. Middleton (1930) observed proportionality between soil loss and the heat of wetting. Bouyoucos (1935) presented that soil loss is proportional to the silt + clay content. Others indicated that the optimum erodibility involved soil permeability, suspension rate, and dispersion rate (Baver, 1933; Pelle, 1937). Then, soil aggregation was increasingly recognized as an important factor of soil erodibility, and the soil aggregate surface ratio (defined as the ratio of the surface area of aggregates ≥ 0.05 mm particles to the soil aggregate content), the >0.25 mm water-stable aggregate percentage, and the rate of disaggregation of water stable aggregates were suggested as soil erodibility indicators (Chuancun, 1979; Lal, 1991; Bajracharya and Lal, 1992).

In China, soil erodibility research began in the 1950s. Zhu (1954) studied the relationship between soil dispersion and the rate of water adsorption by soil. Later Zhu (1960) suggested that permeability is an important factor in soil erosion and that the rate of aggregate disintegration in standing water could be used as an indicator of soil anti-scourability. Tian and Huang (1960) proposed the 1–10 mm aggregate mass, the degree of aggregation, the soil aggregate dispersion rate, and the erosion rate as anti-erodibility indicators for the soils of the Loess Plateau. Wang et al. (1994) indicated that the soil organic matter and clay contents are the principal factors that influenced soil anti-erodibility in the Loess Plateau and that the percentage of water stable aggregates is its best indicator. Yang (1992) proposed the dispersion rate and a soil structure damage ratio as possible indicators of soil erodibility for the soils in the purple soil region (Entisols) in Southeast China. These Chinese studies have provided very useful information for understanding their approach to soil erodibility determinations. They suggest that, except for water stable aggregation, the relevancies of the indicators are based on location-dependent intrinsic soil properties. Although some anti-erodibility and anti-scourability studies were conducted in China in the 1990s, no broadly applicable erodibility parameter was developed. Chinese researchers gradually adapted the USLE (Universal Soil Loss Equation) technology for predicting soil erosion since the 1980s. Nevertheless, the traditional Chinese approaches are still being used in some studies, and the indicators identified have facilitated the development of predictive soil loss relationships.

3.2. Indicators related to exogenic erosional forces

Since the 1940s, numerous studies have been conducted to determine the relationship between soil erodibility coefficients and specific exogenic forces, mostly under controlled experimental conditions. Voznesensky and Artsruui (1940) proposed a scouring erodibility parameter defined as the percentage-by-weight of >0.25 mm aggregates dislodged within 1 h under the scouring action of a water flow rate of 100 cm min^{-1}. Gussak (1946) designed an experiment to evaluate a parameter, similar to the Chinese soil anti-erodibility definition, based on the amount of water needed to erode a unit of soil volume (e.g. 100 cm^3) under different flow velocities. He observed that soil types appreciably affect erosion susceptibility. Ellison (1947) showed that erosion is governed by both detachment and transport processes. That finding has ever since guided soil erosion research in the USA by rainfall and overland flow. Chandra and De (1978), using a simple laboratory overland flow device, found good correlations between a relative erodibility coefficient and other erosion indictors such as the erosion ratio, clay ratio, and silica-sesquioxide ratio for 12 soils. Bryan (1968) and Dusan (1982) summarized the relationship $E = dh/a$, where d is the dispersion rate, h is the water-retaining capacity index, and a is the aggregation index. This relationship firstly connected an intrinsic soil property and an exogenic force, and thus led to the design of the Sobolev Anti-Scour Trench Device and other similar devices for determining soil erodibility (Hudson, 1995).

In the western region of Shaanxi Province, China, Zhu (1954, 1960) used the Sobolev device to examine the traditionally-used anti-erodibility and anti-scourability concepts, by correlating the depth

Table 1
Soil erodibility indicators.

Reference	Soil erodibility indicators	Type	Reference	Soil erodibility indicators	Type
Bennett (1926)	Silica-sesquioxide ratio	[a]	Wischmeier and Mannering (1969), Wischmeier et al. (1971)	≥1 mm sand content, organic matter content, soil structure grade, soil permeability grade, etc.	[a]
Middleton (1930)	Soil wetting heat, erosion rate, dispersion rate	[a]			
Baver (1933)	Permeability indicator	[a]	Chandra and De (1978)	Erosion coefficient	[b]
Bouyoucos (1935)	(sand% + silt%)/clay%	[a]	Shi et al.(1983)	Aggregate dispersivity, water stable indicator	[b]
Pelle (1937)	Permeability rate, suspension rate, dispersion ratio	[a]	Chuancun (1979)	Rate of disaggregation of water stable aggregates	[a]
Voznesensky and Artsruui (1940)	Scouring erodibility parameter	[b]	Li and Liu (1987)	The total water drops which can break up soil particles 7–10 mm in diameter	[b]
Gussak (1946)	Water flow needed to erode 100 g soil	[b]	Laflen et al. (1991a, 1991b)	Relation coefficient	[a]
Ellison (1947)	Soil detachability and soil transportability	[b]	Ekwue (1992)	Soil permeability	[a]
Zhu (1954)	Soil expansion coefficient, still water disintegration	[a]	Yang (1992)	Dispersion rate, erosion rate	[a]
Zhu (1960)	Depth of eroded soil	[b]			
Woodburn and Kozachyn (1956)	Aggregate stability, dispersion rate	[a]	Bajracharya and Lal (1992)	Aggregate stability, anti-scouring intensity	[a], [b]
Olson and Wischmeier (1963)	Soil erodibility factor K	[b]	Zhou and Wu (1993)	Amount of soil loss corresponding to unit runoff depth	[b]
Jiang and Zhu (1962)	Soil amount scoured by unit water amount, scourability coefficient	[b]	Wang et al. (1994)	Water stable aggregate, content of humus and clay	[a]
Tian and Huang (1960)	Total quantity of aggregate, 1–10 mm aggregate amount, degree of aggregation, dispersion degree of aggregate, dispersion rate, erosion rate	[a]	Amezketa et al. (1996)	Soil structure, shear strength	[a], [b]
			An (2000)	≥0.25 mm water-stable aggregate	[a]
Tang (1964)	Soil physicochemical property, mineral composition of clay, microstructure	[a]	Zhao and Shi (2003)	Soil shear strength	[b]

[a] Indicators based on intrinsic soil properties.
[b] Indicators based on exogenic erosive forces.

of eroded soil to rain drop impact (anti-erodibility) and overland flow (anti-scourability). Jiang (1978) improved the scouring test using Gussak's method (1946) with undisturbed soil, and defined the anti-erodibility coefficient as the amount of soil eroded by a unit amount of water under a certain slope gradient and flow rate. Dou (1978) determined the anti-erodibility of loess soil by using the scouring methodology of Jiang (1978) and found consistently similar results among soils that had been in different land uses. Huang (1981) suggested that the soil dispersion rate, erosion rate, clay dispersion index, and aggregation index could be used as anti-erodibility indicators. He also noted that soil anti-erodibility is mainly related to clay content, soil organic matter or soil colloidal properties; while anti-scourability is mainly determined by soil compaction and the amount of roots. The latter finding was corroborated by follow-up studies in the Loess Plateau. Other Chinese studies, suggested that anti-erodibility can be defined in terms of soil aggregate dispersion, water-stable aggregate contents, and soil structure characteristics (Shi et al., 1983; Li and Liu, 1987; Yu and Chen, 1988). Zhou and Wu (1993) suggested the average depth of overland flow as an indicator of the exogenic force for assessing anti-erodibility. Jiang et al. (1995a) proposed $C = Qt/W$ as the anti-scourability parameter, where W is the weight of eroded soil (g), Q is the volume of water required to erode the soil (L), and t is the scouring duration (min). He also indicated that C depends on landforms and conservation practices (Jiang et al., 1995b). In contrast, Zha and He (1999) and Zhao and Shi (2003) suggested that mechanical properties such as soil shear strength better indicate anti-erodibility than the other proposed parameters.

4. Soil erodibility calculations (Quantitative evaluation stage)

Soil erosion and conservation research and studies on the role of topographic, hydrological, culture and soil factors on soil loss began in the 1930s (Wischmeier et al., 1958; Wischmeier, 1959, 1960). Knowledge of soil erodibility was considered critical for soil loss predictions. During the early years (1935–1955), this information was exclusively based on soil loss measurements from natural runoff plots. The development of field rainfall simulators in the 1950s (Meyer and McCune, 1958; Swanson, 1965) greatly facilitated soil erosion research including that of soil erodibility determinations. The effects of various factors and sub-factors could now be determined in a comparatively short time and under standardized conditions. In due brief time, it was realized that process-based erosion prediction equations would greatly enhance the potential of soil loss prediction for situations which could not readily be obtained with the limited capability of the factor-based Universal Soil Loss Equation (USLE). Thus, work began on the Water Erosion Prediction Project (WEPP), a process-based erosion prediction model (Foster and Lane, 1987). This model considers different soil erosion modes on the constituent rill and inter-rill areas that make up the eroding surface. Each one of these areas is dominated by different erosion processes and has therefore its own erodibility coefficient. Work on WEPP is on-going and the model is continuously being updated. During this period, work on the USLE continued as well and has led to an updated version in 1978 (Wischmeier and Smith, 1978), the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) in 1997, and the more scientifically imbued recent update (RUSLE2) of 2003 (USDA-NSL, 2003). RUSLE and WEPP as well as their predecessors are today the most widely used erosion prediction models in the world for upland areas. China has made major efforts and commitments to adapt these models to meet their specific conditions. Therefore, this section mainly focuses on the erodibility coefficients of these two models and also briefs other models in order to provide useful background information for improving erosion prediction and conservation management practices.

Estimates of soil erodibility for recommending conservation practices can be obtained through field measurements such as was done for the USLE by Olson and Wischmeier (1963) or indirectly from existing regression relationships of soil erodibility or from the soil erodibility nomograph (Wischmeier and Mannering, 1969; Wischmeier et al., 1971). The database of the nomograph was collected from field experiments in which several exogenic forces are simultaneously operative. WEPP has modular components of inter-rill and rilling processes, each one of which has its own erodibility coefficient that must be determined. The erodibility coefficients for this model were obtained from small scale field plot experiments (Laflen et al., 1991a, 1991b). In the

USLE field studies, the plots are flat and soil loss measurements represent the integrated effect of all the exogenic forces (rainfall, overland flow, and seepage); while in the WEPP approach the field plots are furrowed. The soil loss is apportioned to the flat side slopes, where inter-rill erosion by rainfall is dominant, and the furrow bottoms where rill erosion by hydraulic shear flow is the dominant erosion mode. Laflen et al. (1991a) showed that, based on small field plot experiments involving 36 cropland soils and 20 rangeland soils, respectively, no satisfactory correlation was found for these soils between the USLE erodibility factor on the one hand; and the WEPP rill and/or inter-rill erodibility coefficients on the other hand. It implied that the present erodibility concept has not been adequately defined yet and establishing standard methods for measuring the erodibility is necessitated.

4.1. USLE soil erodibility factor relationships

The oldest soil erodibility factor database was obtained from 23 major benchmark soil plots in the eastern USA on which soil loss measurements were made in the 1930–1950s under natural rainfall (Wischmeier and Smith, 1965). Seven of these soils were in continuous fallow, the others were in row crops averaging 20 plot years and for which adjustments for the effect of row cropping were made in computing the erodibility factor (Wischmeier and Smith, 1978). The field rainfall simulator facilitated the collection of a significant amount of erodibility factor data (Wischmeier and Mannering, 1969). The database was obtained from 55 mostly medium textured surface soils.

The soils were also analyzed for intrinsic, mostly soil physical properties. This data set became the impetus for the development of the soil erodibility nomograph (Wischmeier et al., 1971) in which five erodibility predictive soil and profile properties were identified: the percent of silt + very fine sand fraction (0.002–0.1 mm), the percent of sand fraction (0.1–2.0 mm), soil organic matter, a code (1–4) for soil structure, and a code (1–6) for soil permeability. The latter codes were defined in the USDA Soil Survey Manual (1951). The silt + very fine sand fraction for these medium-textured soils with relatively poor stability under rainfall impact is more susceptible to transport by runoff than the well structured clay material or coarse sand. The importance of the erodibility nomograph is generally recognized in that it enabled the determination of the erodibility factor from routinely determined standard soil properties and soil profile descriptions. For soils with less than 70% silt plus very fine sand, the nomograph can be expressed by the following relationship (Wischmeier et al., 1971; Wischmeier and Smith, 1978):

$$K = \left[2.1 \times 10^{-4}(12 - OM)M^{1.14} + 3.25(S-2) + 2.5(P-3)\right]/100 \tag{1}$$

where K is the USLE soil erodibility factor, M is the product of percent of silt + very fine sand and the percent of all soil fractions other than clay, OM is soil organic matter content (%), S is the soil structure code, and P is the soil permeability code.

Although the soil erodibility nomograph is widely accepted especially in applications involving medium-textured soils, such as loess soils, its accuracy and usefulness for other soil categories have often been questioned. Therefore, complementary studies using the same type of rainulator and simulation procedures as used for the 55 medium-textured Midwest (USA) soils, were conducted on several other soil categories. Römkens et al. (1975, 1977) tested the applicability of the nomograph for high clay subsoils and found that the nomograph expression did not meet the expected nomograph predictions. They arrived at the relationship:

$$K = 0.004 + 0.00023M - 0.108X_1 \tag{2}$$

where X_1 is the percent of aluminum and ferric oxides ($Al_2O_3 + Fe_2O_3$) extracted by the CDB (citrate–sulfate–carbonate) method. The terms of this equation represent in fact a combination of a textural property and a chemical binding agent. El-Swaify and Dangler (1977) obtained the following relationship for soils derived from volcanic material:

$$K = -0.03970 + 0.00311X_2 + 0.00043M + 0.00185X_3 + 0.00258X_4 - 0.00823X_5 \tag{3}$$

where X_2 is the proportion of unstable aggregates > 0.25 mm (%), X_3 is the water saturation content, X_4 is the redefined silt or silt + very fine sand content (%), and X_5 is the redefined sand fraction (0.01–2 mm). Young and Mutchler (1977) developed the following relationship for Mollisols in western Minnesota, USA:

$$K = -0.204 + 0.385X_6 - 0.013X_7 + 0.247X_8 + 0.003M - 0.005X_9 \tag{4}$$

where X_6 is an aggregation coefficient, X_7 is the percent of montmorillonite clay, X_8 is the average bulk density of the soil profile material between 50 and 125 mm (g cm^{-3}), and X_9 is the soil aggregation dispersion ratio.

From the above relationships, it is apparent that for many soils the erodibility factor in the USLE and RUSLE equations cannot be obtained in a reliable and satisfactory manner from the nomograph. However, it is also evident that soil erodibility can be predicted from a combination of physical soil properties (texture) and chemical/mineralogical parameters. The uncertainty and varied role of binding agents on soil erodibility, given their diversity in type and nature as well as their interactions with the different soil particle sizes and mineralogical properties, make it difficult to arrive at reliable or accurate K-value estimation for unknown soils. Römkens et al. (1986) examined the role of the textural classes on soil erodibility. They used the available erodibility factor database obtained from both natural runoff plots and simulated rainfall studies and considered only the particle size properties in the analysis. They computed from each soil the geometric mean diameter (Dg) in mm according to the expression:

$$Dg = \exp\left(0.01 \times \sum_{i=1}^{n} f_i \ln m_i\right) \tag{5}$$

where f_i is the weight percentage of the i-th particle size fraction (%); m_i is the arithmetic mean of the particle size limits for the i-th fraction (mm); and n is the number of particle size fractions (Shirazi and Boersma, 1984). Ten size classes were chosen for 225 global soils and 138 soils of USA, respectively. The relationships between the soil erodibility factor K and log Dg can be approximated using the following two exponential functions with R^2 values of 0.98 and 0.95, respectively (Römkens et al., 1997):

$$K = 7.594\left\{0.0034 + 0.0387 \exp\left[-\frac{1}{2}\left(\frac{\log(Dg) + 1.533}{0.7671}\right)^2\right]\right\} \tag{6}$$

for the 225 global soil populations

$$K = 7.594\left\{0.0017 + 0.0494 \exp\left[-\frac{1}{2}\left(\frac{\log(Dg) + 1.675}{0.6986}\right)^2\right]\right\} \tag{7}$$

for the 138 American soils.

In China, researchers introduced and applied the USLE approach in the late 1980s, and then estimated erodibility values for the main Chinese soils (Table 2). For instance, Lü and Shen (1992) calculated K-values for the main agricultural soils in South China by interpolating a transformed soil texture data set with a quadratic spline function. The results were then combined with experimentally acquired erodibility factor values. The highest erodibility value was obtained for the red soils developed from Quaternary red clay, which has a heavier texture and is more enriched in sesquioxide than granite, followed by purple soils derived from sand-shale. Red soils developed from the granite presented the lowest K-value. Shi et al. (1995, 1997) and Xing et al. (1998) conducted similar field studies on the erodibility of seven typical soils of the subtropical region in Jiangxi Province

Table 2
Soil erodibility values from typical studies in China.

Reference	Location	Soil type	Calculation method	Soil erodibility *K*-value	Unit	Remark
Zhang et al. (1992)	Heilongjiang province	Black soil	USLE	0.26	t ha^{-1}	$R=E_{60}I_{30}$ Slope = 9°
		Dark brown soil		0.28		
		Plano sol		0.31		
Jin et al. (1992)	Inner Mongolia	Loess	USLE	0.02	t hm^2 h hm^{-2} MJ^{-1} mm^{-1}	Slope = 6°
		Feldspathic sandstone		0.03		
		Sandy loess		0.015		
		Aeolian sandy soil		0.0075		
Lü and Shen (1992)	Southern China	Red soil	EPIC	0.29–0.38	t acre h (100 acre)$^{-1}$ ft^{-1} t^{-1} in.$^{-1}$	Only analyzed by using soil organic carbon and soil particles, without verification by using a measured value
		Huangyan Soil		0.22–0.25		
		Yellow red soil		0.25		
		Yellow soil		0.26		
		Mountain shrubby meadow soil		0.30		
		Yellow brown Soil		0.33		
		Purple soil		0.37		
		Acid purple soil		0.20		
Zhou and Wu (1993)	the Loess Plateau	Loess	Soil loss/ runoff depth	0.0713–0.4467	kg m^{-2} mm^{-1}	Plot measurement
Wu et al. (1993)	the Loess Plateau (Tianshui)	Loess	Soil loss/ runoff depth	0.007–0.302	kg m^{-2} mm^{-1}	Plot measurement
Bu and Li (1994)	Zhangjiakou of Hebei province	Clay	Similar to USLE	0.21	(sh t.) acre h (100 acre)$^{-1}$ ft^{-1} (sh t.)$^{-1}$ in.$^{-1}$	Calculated by using method of searching chart, without verification by using a measured value
		Clay loam		0.28		
		Loam		0.38		
		Sandy loam		0.27		
		Sand		0.05		
Jiang et al. (1995a, 1995b)	the Loess Plateau	Loess	Qt/W	0.01–0.544	L s g^{-1}	Scouring experiment
Shi et al. (1997)	Yingtan of Jiangxi province	Red soil	USLE	0.104	0.132 t h MJ^{-1} mm^{-1}	Natural rainfall $R=EI_{30}$ plot size = 12 m^2
		Common red soil		0.232–0.438		
		Purple soil		0.440		
		Quasi Red Soil		0.256		
Yu et al. (1997)	Yingtan of Jiangxi province	Red soil	USLE	0.135–0.181	(sh t.) h(100 ft)$^{-1}$ (sh t.$^{-1}$)in.$^{-1}$	Simulated rainfall, mode III
		Common red soil		0.045–0.373		
		Purple soil		0.322–0.327		
		Quasi red soil		0.171–0.223		
Lin et al. (1997)	Liaoning province	Loessial brown soil	Nomograph	0.36–0.38		
Liu (1999)	Zhaotong dam area of Yunnan province	Hydromorphic paddy soil	USLE	0.39–0.43	t hm^{-2} a^{-1}	$R=EI_{15}$
		Gley paddy soil		0.51–0.56		
		Submerged paddy soil		0.31–0.35		
		Mountain yellow soil		0.50–0.58		
		Purple soil		0.55–0.59		
Yang (1999)	Northeast mountain region of Yunnan province	Red soil	USLE	0.360	t hm^{-2} a^{-1}	Slope = 5° $R=E_{60}I_{30}$
		Yellow soil		0.301		
		Purple soil		0.410		
Liang and Shi (1999)	East Hilly area of the Southern Yangtze River	Latosol	USLE	0.228	The unit was not given	Calculated by using soil texture transformation, without verification by using a measured value
		Red soil		0.231		
		Yellow soil		0.191		
		Yellow brown soil		0.219		
		Purple soil		0.343		
Bu et al. (2002)	Tai lake basin	Yellow white soil	USLE	0.4792	(sh t.) acre h (100 acre)$^{-1}$ ft^{-1} (sh t.)$^{-1}$ in.$^{-1}$	Without verification by using a measured value
		Silt		0.4612		
		Yellow mud soil		0.3344		
		Skeleton soil		0.2277		
		Yellow brown soil		0.0559		
		Erodibility lateritic red soil		0.226		
		Yellow sandy soil		0.323		

using rainfall simulations. Their results indicate that the erodibility factor was greatest for a silt loam soil and lowest for a loamy clay soil. Yang (1999) developed a revised nomograph equation based on many years of data from cultivated natural runoff plots obtained from the northeast mountainous region of Yun'nan Province:

$$K=\left[2.737\times10^{-4}(12-OM)M^{1.14}+4.236(S-2)+2.259(P-3)\right]/100. \tag{8}$$

The form of Eq. (8) is more suitable for many applications in Southwest China. Yu et al. (1997), Yu and Shi (2000), Cai et al. (2000), and Zhang et al. (2008) conducted rainfall simulation studies on soil erodibility of the important soil series from the four main soil regions in China: the black soil region in NE China, the loess soil region in NW China, the purple soil region in SW China, and the red soil region in South China. They took into account and adjusted for both the effect of simulated rainfall characteristics and the rain infiltration on soil loss. Yu et al. (1997) and Yu and Shi (2000) found that the acquired soil erodibility factors were more reliable if rainfall was intermittently applied. Wang et al. (2012), using a Chinese erodibility database from the four main soil regions, obtained good agreement between the global erodibility factor relationship derived by Römkens et al. (1997) for textural properties and the Loess plateau data set. He also developed a *Dg*–*OM* relationship which permitted better parameterization and accuracy, and was proved to be suitable for estimating soil erodibility values in China:

$$\begin{aligned}K={}&0.0364-0.0013[\ln(OM/Dg)-5.6706]^2\\&-0.015\exp\left[-28.9589(\log(Dg)+1.827)^2\right].\end{aligned} \tag{9}$$

Those experiences not only greatly expend the application scope of the USLE approach, especially for the steep slope condition and silt/sandy soils; but also provide available abundant and full-scale databases for international soil erodibility research.

4.2. WEPP soil erodibility coefficients

The dependence of soil erosion prediction and soil conservation programs for upland areas on USLE/RUSLE technology, while very useful for a given locality with its specific conditions, is not always adequate when predictions need to be made for different situations involving different soils, land uses, cropping practices, and topographies elsewhere. The parameters and the regression type relationships obtained are often not transferable. While the USLE has been a tremendous conservation management tool, the desire was to develop process based relationships that would include many physically based sub-processes. Such a relationship would have a greater universality and applicability and would cover a wider range of conditions and situations. WEPP (Water Erosion Prediction Project) meets those requirements.

The development of the process based WEPP model began in the mid-1980s (Nearing et al., 1989a; Laflen et al., 1991a, 1991b; Flanagan and Nearing, 1995). The first edition was published in 1995, and the latest in 2010 (USDA-ARS-NSERL, 2010). WEPP is a continuous simulation model that uses a steady state continuity equation that represents detachment, transport, and deposition processes. The WEPP model is based on the concept that erosion takes place by two different but complementary sub-processes: inter-rill and rill erosion (Foster and Meyer, 1972). The first mechanism is mostly driven by rainfall through splash and sheet or shallow overland or film flow; while the second mechanism is driven by concentrated flow or shear flow. Each of these sub-processes has their own erodibility coefficient, K_i and K_r, respectively. K_i is a measure of the soil delivery rate to the rill–gully–channel system following detachment by raindrop impact and transport by splash and shallow overland flow (Laflen et al., 1991a, 1991b; Flanagan and Nearing, 1995); K_r is a measure of the soil susceptibility to detachment by concentrated flow (Flanagan and Nearing, 1995). In both cases, soil as well as hydrologic and hydraulic properties plays an important role, such as soil particle size and size distribution, surface micro-roughness, soil binding agents like organic carbon and other chemical constituents on the one hand, and flow regime properties such as shear stress, and its critical flow, on the other hand. It is evident that the multiple factors and constituents call for practical parameters, which integrate the role and effect of many of these processes. Therefore, many studies were conducted in which correlations were sought among many of the aforementioned process-related soil properties of which we know that they affect erodibility.

Field experiments were conducted in 1987 and 1988 (Laflen et al., 1987; Simanton et al., 1987; Elliot et al., 1989) to establish baseline values for inter-rill (K_ib) and rill erodibility (K_rb) coefficients for cropland and rangeland conditions. Also, a baseline critical hydraulic shear stress, τ_cb, was determined as needed for calculating the critical rill erodibility coefficient. The database was grouped into two classes of soil having more or less than 30% sand for which equations were obtained (Nearing et al., 1989b; Liu and Shi, 1992; Xie et al., 2003; Zheng et al., 2004; Zhang and Liu, 2005). For cropland with more than 30% sand, the equations for baseline inter-rill erodibility (K_ib), baseline critical rill erodibility (K_rb), and baseline critical hydraulic shear stress (τ_cb) are:

$$K_\mathrm{ib} = 2.728 \times 10^6 + 1.921 \times 10^7 vfs \tag{10}$$

$$K_\mathrm{rb} = 0.00197 + 0.030 vfs + 0.03863 e^{-1840M} \tag{11}$$

$$\tau_\mathrm{cb} = 2.67 + 6.5 clay - 5.8 vfs \tag{12}$$

where *vfs* is the very fine sand content (%), and *clay* is the clay content (%). For cropland soils containing less than 30% sand, the equations are as follows:

$$K_\mathrm{ib} = 6.054 \times 10^6 - 5.513 \times 10^6 clay \tag{13}$$

$$K_\mathrm{rb} = 0.0069 + 0.134 e^{-20clay} \tag{14}$$

$$\tau_\mathrm{cb} = 3.5 \tag{15}$$

The WEPP model was validated against a large soil loss dataset obtained from many locations in the USA and other countries (Flanagan and Nearing, 1995; Bulygin et al., 2002; Nearing et al., 2005). Because of this extensive and broadly based validation effort, the WEPP model can be applied to many un-gaged areas (Zhang et al., 1996; Laflen et al., 2004; Bulygina et al., 2007), and can accommodate with a considerable measure of confidence spatial and temporal variations relative to soil properties, topography, hydrology, and land uses. In addition, the baseline inter-rill and rill erodibility coefficients can be internally adjusted by a daily step set of multiplication factors, which would account for the temporal variability. These factors are different for cropland and rangeland. For cropland, the adjustment factors for K_ib include canopy effects, groundcover, live and dead root biomass, sealing and crusting, inter-rill slope, and freeze–thaw effects. The adjustment factors for K_rb include incorporated residue, roots, sealing and crusting, and freeze–thaw effects. While for rangeland, the adjustment factors for K_ib and K_rb were ground cover and freeze–thaw, respectively (Flanagan and Nearing, 1995).

Numerous validation studies of the WEPP model have been conducted around the world especially for hillslope hydrology, erosion factors, and soil properties (Nearing et al., 1989b; Klik et al., 1995; Zhang et al., 1996, 2004; Bjorneberg et al., 1999; Tiwari et al., 2000; Laflen et al., 2004; Lei et al., 2008; Truman et al., 2009). These studies indicated that WEPP performs rather well over a wide range of soils and soil conditions, although soil erodibility parameters in WEPP may not be suitable for furrow irrigation (Laflen et al., 2004). Also, some research findings have indicated that the K_ib and K_rb erodibility coefficients in WEPP were relatively high for sandy soils (Flanagan and Nearing, 1995; Tiwari et al., 2000; Duiker et al., 2001; Romero et al., 2007; Truman et al., 2009) as compared to those obtained from the USLE soil erodibility nomograph (Declercq and Poesen, 1992; Klik and Zartl, 2001; Zhang et al., 2008; Wang, 2009). The observed differences were attributed to the manner in which the various sub-processes were accounted for. The WEPP model separates fundamental processes such as infiltration, detachment, and transport, while the USLE lumps these processes together (Laflen et al., 1991a; Tiwari et al., 2000; Truman et al., 2009). Comparative studies of the values of the soil erodibility parameters of the USLE, RUSLE, and WEPP models were also conducted (Laflen et al., 1991a, 1991b, 2004; Liu et al., 1999; Tiwari et al., 2000; Bulygin et al., 2002; Miao et al., 2004). These studies conclude that there was virtually no correlation between the USLE/RUSLE erodibility factors and the WEPP erodibility coefficients due to the conceptual differences in the manner that the component processes were considered in these models.

4.3. Erodibility coefficients in other erosion models

From the 1980s to the present major other erosion prediction models were developed around the world that reflected different views or served different local erosion conditions and conservation needs. These include CREAMS (Knisel, 1980), EUROSEM (Morgan et al., 1998), and GUEST (Misra and Rose, 1996). CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) was the first model to separate rill and inter-rill erosion processes (Foster et al., 1980). EUROSEM (European Soil Erosion Model) is a distributed event-based model (Abbott et al., 1986). GUEST (Griffith University Erosion System Template) is a steady-state, process based model that was developed to account for temporal fluctuations in sediment concentrations from bare soils during single erosion events (Misra and Rose, 1996; Rose et al., 1997). All these models have independent erodibility coefficients. CREAMS still relies on the USLE *K*-factor (Knisel, 1980; Flanagan, 2004). EUROSEM has the coefficients EROD (a measure of soil detachability by rain drop impact) and COH (a measure of soil erosion expressed in terms of detachability by surface flow). GUEST considers sheet and rill erosion processes similar to WEPP, in which an event-based erodibility parameter was considered that related the sediment concentration at the transport limit to the actual sediment concentration (Rose, 1993; Yu and Rose, 1999).

5. Temporal and spatial variations of soil erodibility

5.1. Spatial variation of soil erodibility

Many publications consider soil erodibility as a year-around constant parameter for a given soil (e.g., Middleton, 1930; Bouyoucos, 1935; Hudson, 1995) and indicate that soil erodibility can be determined from stable soil properties (Römkens, 1985; Bryan, et al., 1989; Lal, 1991; Liu et al., 1999). Other studies have indicated that soil erodibility varied for a given soil as a function of location, climate change, and human activity (Mutchler and Carter, 1983; Bajracharya and Lal, 1992; Rejman et al., 1998; Zhang et al., 2001b; Torri et al., 2006; Salvador Sanchis et al., 2007). Therefore, soil erodibility should be considered as a non-constant term that varies in space and time. In the 1970s, research began to focus on the spatial variation of soil erodibility, a notion that had become increasingly accepted in field erosion.

5.2. Temporal variation of soil erodibility

Although spatial variations in soil erodibility coefficients can be easily detected by observing variations in soil erodibility properties within the landscape, temporal variations due to wetting and drying effects and freeze and thawing cycles are more difficult to detect. Because of the large difference in soil erosion between dry and wet seasons, seasonal *K*-values should be calculated to obtain reasonable and accurate USLE-based predictions (El-Swaify and Dangler, 1977; Hosoyamada, 1986). Misra and Teixeira (2001) conducted simulated rainfall studies to determine the change in erodibility between dried and wetted soils but concluded that the change, while discernible, was difficult to predict because of soil shear strength changes. Giovannini et al. (2001) showed that prolonged droughts between rainstorms led to a significant change in soil erodibility. Moreover, Tang (2004) indicated that soil structure and aggregate stability, principal determinants of soil erodibility, were sensitive to the effects of successive drying and wetting.

Others conducted research on the dynamics of soil erodibility due to changes in temperature and the effect of freeze–thaw processes on soil properties. Mutchler and Carter (1983) studied six years of natural runoff plot data from Minnesota, USA and found that annual and seasonal variations in the soil erodibility factor could be described by a cosine function with two extreme values. These extremes were 1.69 and 0.31 times the average annual mean value of the soil erodibility in February and August, respectively. They also indicated that soil erodibility was highly correlated with temperature change. Kirby and Mehuys (1987a, 1987b) made similar findings with soils in south-western Quebec, Canada. They attributed the extremes to the frozen subsoil that allowed the development of a saturated surface layer on the top of soil upon thawing and thus increasing the erosion rate. Coote et al. (1988) indicated that soil was more readily eroded during the spring thaw when the soil was wetter than in the growing season. They also suggested that the main factors affecting soil erodibility were soil shear strength, aggregate stability and their temporal variations. They furthermore suggested that the soil water content and temperature regimes did influence the re-aggregation of soil particles and their subsequent enhanced ability to resist exogenic soil erosional forces. Others (Bryan, 1971; Van Vliet and Wall, 1981; Bajracharya and Lal, 1992; Rejman et al., 1998; Zhang et al., 2001a; Parysow et al., 2003) came to similar conclusions and proposed that the increases in soil erodibility were due to: (i) decreases in the percentage of water stable aggregation, and (ii) increases in the surface water content due to snow melt. A tentative solution for improving the accuracy of soil erodibility calculations was also proposed by Torri et al. (1997, 2002) and Salvador Sanchis et al. (2007), who studied the effect of climatic factors on the change in soil erodibility. Based on an analysis of monthly mean soil erodibility data, they showed that the local climate type had a strong effect on soil erodibility.

The soil erodibility nomograph does not reflect climatic effects on soil erodibility. Therefore, in RUSLE2 the effect of temporal soil erodibility variations were taken into account by including the summer, winter, and mixed winter–summer modules for *K*-value calculations (USDA-ARS, 2008). The temporal soil erodibility equation of RUSLE2 for summer conditions could be used for all USA locations except the Req zone where soil erodibility increases during the winter season. The RUSLE2 Science Documentation Manual (USDA-ARS, 2008) contains the temporal soil erodibility relationships for the winter as well as combined summer–winter periods.

6. Research challenges

Although substantial progress has been made in describing the relationship between soil erodibility and erosional exogenic forces, significant gaps and challenges remain. Some of these concerns are listed below:

(1) The soil erodibility concept has not been adequately defined. Soil erodibility relative to soil particle bonding mechanisms and detachment is still not well understood. Because the definition of soil erodibility was developed from field measurements rather than theoretical considerations, soil erodibility has been described as the general susceptibility to the detachment and transport of soil particles due to the combined effects of exogenic erosional forces rather than the response to specific erosion sub-processes, such as rain splash, sheet erosion, and rilling. Therefore, the constraints and limitations that exist in the use and application of soil erodibility evaluations have often been ignored. Consequently, even with full knowledge of topographic and land use factors, the impact of soil erodibility on soil loss computations retains some degree of uncertainty.

(2) Methodology and calibrations for soil erodibility coefficients of different erosional sub-processes and geographical areas need to be improved. USLE/RUSLE-based soil erodibility factors, especially those suggested in the soil erodibility nomograph, are widely used without determining the appropriateness of these values for the relevant situations and soil type. For instance, USLE/RUSLE2's Scientific Manual (USDA-ARS, 2008) provides a database for suitable profile permeability classes based on soil surveys of the USDA Bureau of Plant Ind., Soils, and Agr. Eng. (1951). However, profile permeabilities vary by location and condition (e.g., surface sealing and crusting). Thus, the accuracy of the soil erodibility factor for a given situation or application is often uncertain, especially when the evaluated soil differs from those in the database.

(3) More information on the temporal variation of soil erodibility coefficients is needed, and their values in relation to long-term land use practices must be determined. Although temporal variations are generally recognized, the underlying causes and factors are not fully understood (Wischmeier and Mannering, 1969; Mutchler and Carter, 1983; Zhang et al., 2001a; Liu and Liu, 2007). Some of these changes are closely associated with human activities (Wischmeier and Mannering, 1969; Liu, 1999) and the intensity and pattern of erosive forces. Unfortunately, little research on these aspects is currently being conducted.

(4) Current soil erodibility research in China still focuses primarily on anti-scourability, and exploratory studies on predictive models of erodibility are relatively rare. Furthermore, the results of this research are contradictory, and knowledge on the mechanism of soil detachment is scarce. Future progress in understanding the underlying mechanism of erodibility will require advanced and standardized methodology to measure and estimate soil erodibility in relation to different erosional sub-processes.

(5) Although much progress in quantifying soil erodibility in upland areas has been made in the USA, methods to quantify the erodibility of land with significant head cuts and/or ephemeral gully erosion problems remain lacking. These situations pose serious research challenges in relation to erodibility determinations. Moreover, the erosion issues are usually confounded by internal stability problems due to seepage. Considering the recent developments on the relationship between seepage and erosion, a formulation of erodibility separating the seepage effect should be proposed.

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