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RESEARCH ARTICLE

Assessment of soil erosion under woodlands using USLE in China

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Abstract Universal Soil Loss Equation (USLE), originally developed by the USDA for agricultural lands and then used throughout the world, was applied in mountainous forest terrain in China. The woodland area was divide into 100 m × 100 m grid cells. The ArcInfo 9.2 GIS software provided spatial input data was used to predict the spatial distribution of the average annual soil loss on grid basis. The average rainfall erositivity factor (*R*) for national woodlands was found to be 21–1798 $\mathrm{MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot a^{-1}}$. The soil erodibility factor (*K*) with a magnitude of 0.043 $\mathrm{t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}}$ is the highest for Chinese woodland. Most of the slope length factors (*LS*) were less than 5 for the national woodland. The highest and lowest values of cover and management factor (*C*) were found out to be 0.0068 and 0.2550 respectively for coniferous woodland and orchard woodland. The value of conservation factor (*P*) was assigned to be 1 for Chinese woodlands because of scarcity of conversation practice data at the national scale. The average annual soil loss of the national woodland areas was 3.82 $\mathrm{t \cdot km^{-2} \cdot a^{-1}}$. About 99.89% of Chinese woodland area was found out to be under slight erosion class, whereas it only resulted in about 41.97% of soil loss under woodland area, and 58.03% of soil loss occurred under high erosion potential zone, namely more than 5 $\mathrm{t \cdot ha^{-1} \cdot a^{-1}}$. Therefore, those zones need immediate attention from soil conservation point of view. The results here are consistent with many domestic and oversea previous researches under mountainous forests or hilly catchments, thus we showed that the USLE can be applied to estimations of soil erosion for Chinese woodlands at the national scale.

Keywords conservation factor, cover and management factors, slope length factor, soil erodibility factor, Universal Soil Loss Equation (USLE), woodland, soil erosion

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1 Introduction

Forests also play a major role in moderating soil and ecosystem hydrology and water balance while providing wood, fuel, food, fodder, medicines, and other products (e.g. dyes, tannins, perfumes, ornamentals, exudates) (Blanco and Lal, 2008). Previous study showed that undisturbed perennial woodlands generally produce the least amount (normally ranges from 0.02 to 1.2 $\mathrm{mg \cdot ha^{-1}}$) of runoff and soil erosion among all land use systems (Wagenbrenner et al., 2006). Forests reduce soil erosion by forming a dense and multistory canopy with thick forest floor litter and extensive root system. These characteristics not only intercept and diminish rain and wind energy (Pimentel and Kounang, 1998), but also capture and sponge up raindrops, store rainwater, and release water through seepage at non-erosive velocities, and protect the soil from the direct impact of raindrops and throughfall (Blanco and Lal, 2008).

The Universal Soil Loss Equation (USLE) technology is a simple empirical model for erosion prediction (Wischmeier and Smith, 1978), it has been widely applied to agricultural lands in many nations. Several investigators (Lu and Shen, 1992; Huang et al., 1993; Tan et al., 2005; Wang and Zhang, 1995; Wang and Jiao, 1996; Yang, 1999; Yu et al., 2006) evaluated the USLE for farmland in China, and recommended improvements based on their studies.

Although the application of USLE technology to erosion prediction in forests has been, however, limited for it does not accurately capture the complex forest landscapes (e.g., steep slopes, rugged topography) (Sheridan and Rosewell, 2003; Elliot, 2004), while, with the development of GIS and remote sensing, which are used to gather, store and provide information on forest cover, soil data and digital elevations required to create cover-management factor, soil erodibility factor, and topographic maps for the USLE, some studies have applied the USLE to predict soil erosion of forest terrains. Dissmeyer and Foster (1980) used the

USLE in forest environments by developing a sub-factor procedure for cover factor estimation, and Özhan et al. (2005) have computed the cropping management (*C*) and the support practice (*P*) factors of the equation together in a single numerical value as a cover and management factor (*CP*) of the USLE for forest terrains. Yin et al. (2007) estimated the rainfall erosivity using 5- to 60-min fixed-interval rainfall data from China. It is a trend that USLE was used in combination with GIS and remote sensing in predicting soil erosion of woodlands (Sun and Mcnulty, 1998; Lee, 2004; Shi et al., 2004; Dabral et al., 2008; Zhou and Wu, 2008).

Although, many precise data sets of field erosion tests and some successful applications of USLE in predicating the soil erosion for mountainous forests have been achieved at the regional scale in China, there is no large-scale test to estimate soil loss for national mountainous forests. Considering conventional methods of soil loss estimation are time-consuming, costly, and biased especially for mountainous forest. To recognize the service value of Chinese forests in decreasing soil erosion, we will study the application of USLE to national mountainous forests, and test its reliability using the previous researches at home and abroad.

2 Materials and methods

2.1 Data

To apply the USLE, a spatial database including precipitation, topography, soil, and plant distribution was constructed (Table 1), and the distributions of Chinese woodland and its digital elevation model (DEM) are respectively shown in Figs. 1 and 2. Those data are available in China as a digital data. There are six factors to be considered in calculating soil erosion and those factors were estimated from the spatial database. The average precipitation data of 1968–1999 at a 1∶1000000 scale and soil data at a 1∶1000000 scale used in estimated respectively the rainfall erosivity factor (*R*) and soil erodibility factor (*K*) were obtained from Chinese natural resources database. The digital elevation model (DEM) with a spatial resolution of 90 m × 90 m used in calculating slope length and steepness factor (*LS*) were from the data sharing infrastructure of earth system science. The forest data was obtained from plant distribution (1999) at a 1∶1000000 scale achieved by the Institute of Botany, the Chinese Academy of Sciences. The cover and management factor (*C*) were estimated according to forest data, and conservation practice factor (*P*) equal to 1 for scarce data of Chinese conservation practice at the national scale. Then, we converted those factor data into raster format with spatial resolution of 100 m × 100 m using ESRI's ArcGIS9.2 spatial analyst module.

2.2 USLE

USLE was used to determine the average annual soil loss and its spatial distribution on the watershed. The USLE predicts soil loss for a given site as a product of six major erosion factors (Eq. (1)), whose values at aparticular location can be expressed numerically. The values of these erosion factors vary considerably about their means from event to event, but the effects of these fluctuations average out in the long run. The limitation of this model is that it does not estimate deposition, sediment yield, channel erosion, or gulley erosion. Thus, the USLE is suitable for predicting long-term averages, and the soil erosion is estimated as follows:

$$A = R \times K \times LS \times C \times P, \tag{1}$$

where A is average annual soil loss rate ($t \cdot ha^{-1} \cdot a^{-1}$), R is rainfall erosivity factor ($MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot a^{-1}$), K is soil erodibility factor ($t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$), LS is topographic factor, C is crop management factor, and P is conservation supporting practice factor. In the present study, average annual soil loss was estimated on a 100 m × 100 m cell basis resolution by overlaying the five digital parameter layers (*R*, *K*, *LS*, *C*, *P*) in vector format. Here, each cell is assumed as a closed plot where surface flow cannot enter a cell from another cell. Similar assumption was made by Fistikoglu and Harmancioglu (2002).

3 Factors in USLE model

3.1 Rainfall factor (*R*)

Rainfall erosivity, the *R*-factor computed originally from rainfall amount and intensity represents the erosivity of the climate at a particular location. Many researches have tried to establish relationships between the *R*-factor and available precipitation data (such as monthly, annual total

Table 1 Data layer of study area

Classification	GIS data type	Scale
Plant distribution	Polygon coverage	1∶1000000
Precipitation	Polygon coverage	1∶1000000
Soil data	Polygon coverage	1∶1000000
The digital elevation model	Gird	90 m × 90 m

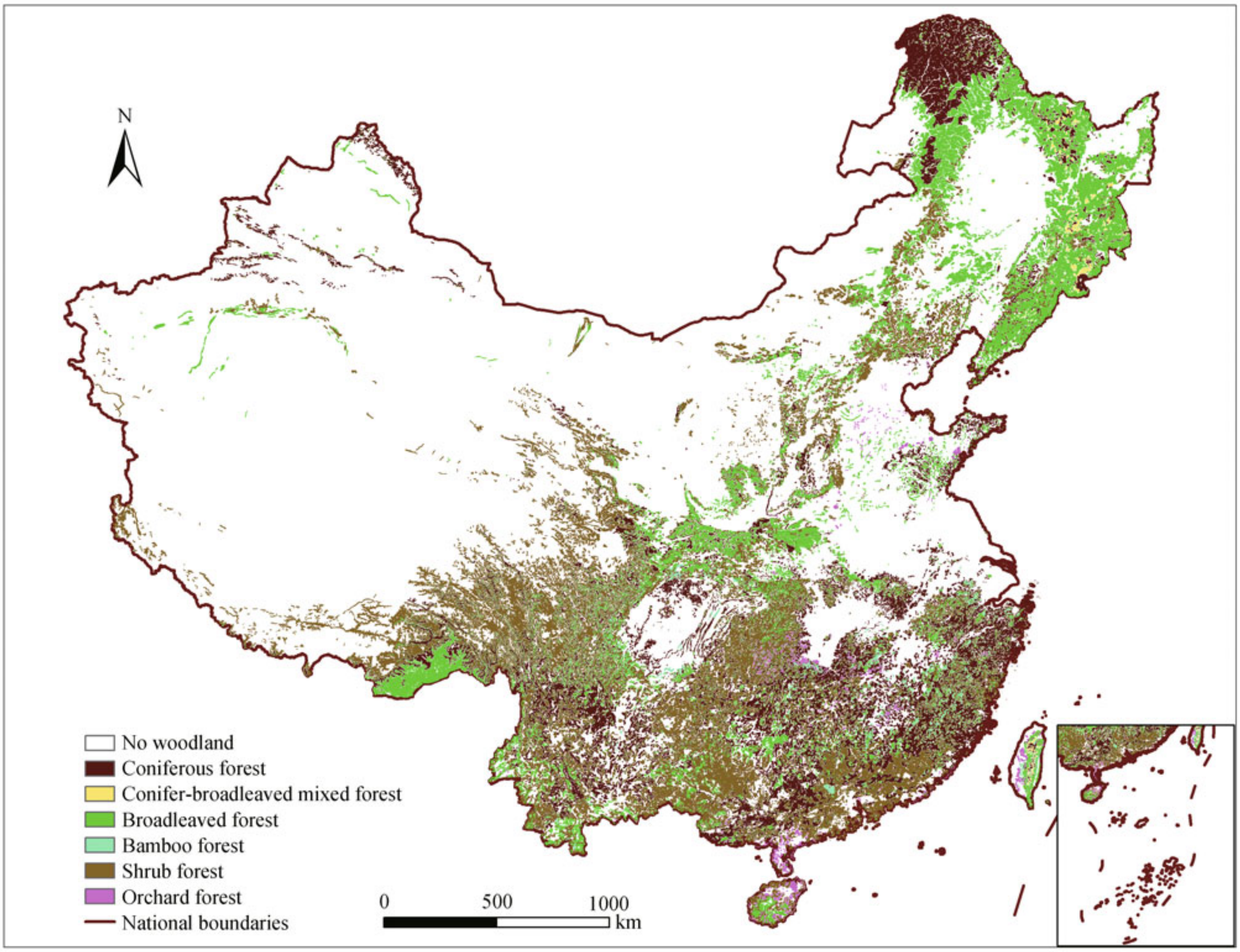

Fig. 1 Spatial distribution of forest types

precipitation and the storm's maximum 30-min intensity) to overcome the obstacle of computing regional *R*-factors without sufficient long-term records of rainfall intensity (Renard and freimund, 1994; Wang and Jiao, 1996; Renard et al., 1997). Renard and Freimund (1994) examined a national data set of the rainfall erosivity factors from 155 stations in the United States. Using annual rainfall data, a regression equation for calculating the rainfall erosivity factor was proposed as:

$$R = 0.0483P_a^{1.610}, P_a \leqslant 850 \text{ mm},$$

$$R = 587.8 - 1.219P_a + 0.004105P_a^2, P_a > 850 \text{ mm}, \quad (2)$$

where R = rainfall erosivity factor in $\text{MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}\cdot\text{a}^{-1}$, P_a = annual rainfall in mm. Another method of estimating the rainfall erosivity factor was developed by Wischmeier and Smith (1978):

$$R = \sum_{i=1}^{12} 1.735 \times 10^{1.5\times\log_{10}\left(P_i^2/P\right) - 0.08188}, \quad (3)$$

where, R = rainfall erosivity factor in $\text{MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}\cdot\text{a}^{-1}$, P_i = monthly rainfall in mm and P = annual rainfall in mm. To obtain regional relationships between rainfall erosivity and annual precipitation, several studies performed in regions of China have been reviewed (Bu et al., 1992; Huang et al., 1993; Liu, 1993; Zhou et al., 1995). But these studies used different periods and lengths of data records over different regions, and Eq. (3) is better than Eq. (2) for it taken monthly rainfall into account. Therefore, this research uses the Eq. (3) only for calculating Chinese rainfall erosivity. Although it might introduce some errors for regions which have different climate characteristics from North America, while, it can offer a uniform standard for evaluating Chinese rainfall erosivity, and Dabral et al. (2008) have achieved good effects in using it evaluate soil erosion in a hilly catchment of North Eastern India. The results, in the form of the *R*-factor map and its distribution percentage, are shown in Fig. 3 and Table 3.

3.2 Soil erodibility factor (*K*)

The *K* factor represents average long-term soil and

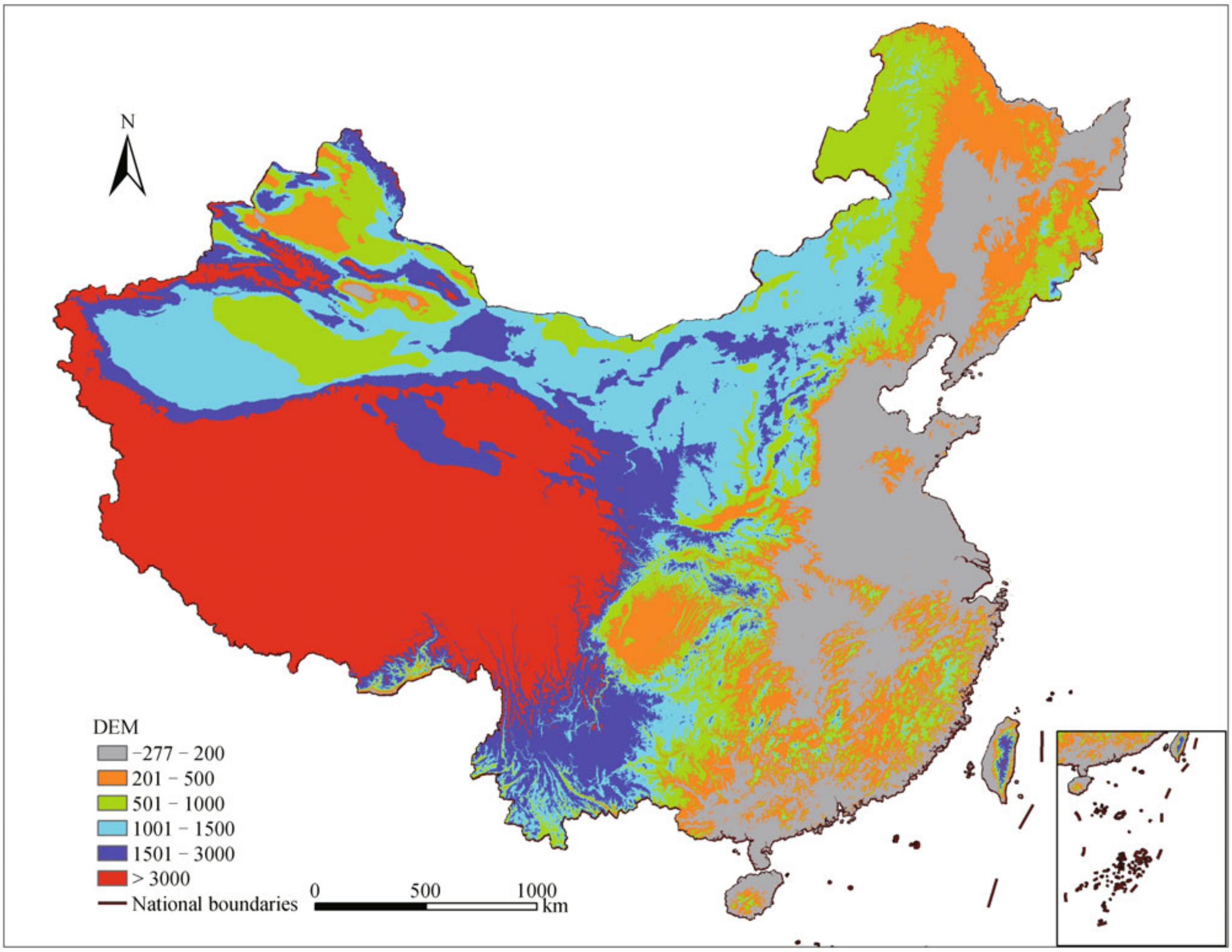

Fig. 2 Spatial distribution of Chinese DEM

soil-profile response to the erosive power associated with rainfall and runoff. The USLE estimates the K factor of agricultural land was using homograph method (Wischmeier and Smith, 1978). However, the ground surface of mountainous forest is covered by the litter layer underlaid with stratified layers of mineral soil. The erodibility of soil in mature forests is likely influenced more thoroughly by environmental conditions, such as soil moisture, temperature and the character of forest letters, than by parent materials; nevertheless, such relationships have not been studied. Wischmeier et al. (1971) found that K values can be estimated using soil properties that are most closely correlated with soil erodibility (Song et al., 2005), These soil parameters are soil texture, content of organic matter, soil structure and permeability. Another method of estimating the soil erodibility factor used in the EPIC model (Sharply and Williams, 1990) is employed for a simple verification. In the EPIC model, water erosion is calculated using the USLE and K is estimated by

$$K = \frac{1}{7.6}\left\{0.2 + 0.3\exp\left[-0.256SAN\left(1-\frac{SIL}{100}\right)\right]\right\} \left[\frac{SIL}{CLA + SIL}\right]^{0.3}\left(\frac{1-0.25OM}{OM + \exp(3.72-2.995OM)}\right) \left(1-\frac{0.7SN}{SN + \exp(-5.51 + 22.9SN)}\right), \quad (4)$$

where K = soil erodibility factor, $\mathrm{t\cdot h \cdot ha^{-1}\cdot MJ^{-1}\cdot mm^{-1}}$, $SN = 1-SAN/100$ and SAN, SIL, CLA and OM are the percentage content of sand, silt, clay, and organic matter, respectively.

The determination of K values for forest hillslope is difficult because of scarcity data of soil texture, soil structure and permeability at the national scale in China. We used Eq. (4) for calculating the soil erodibility. The

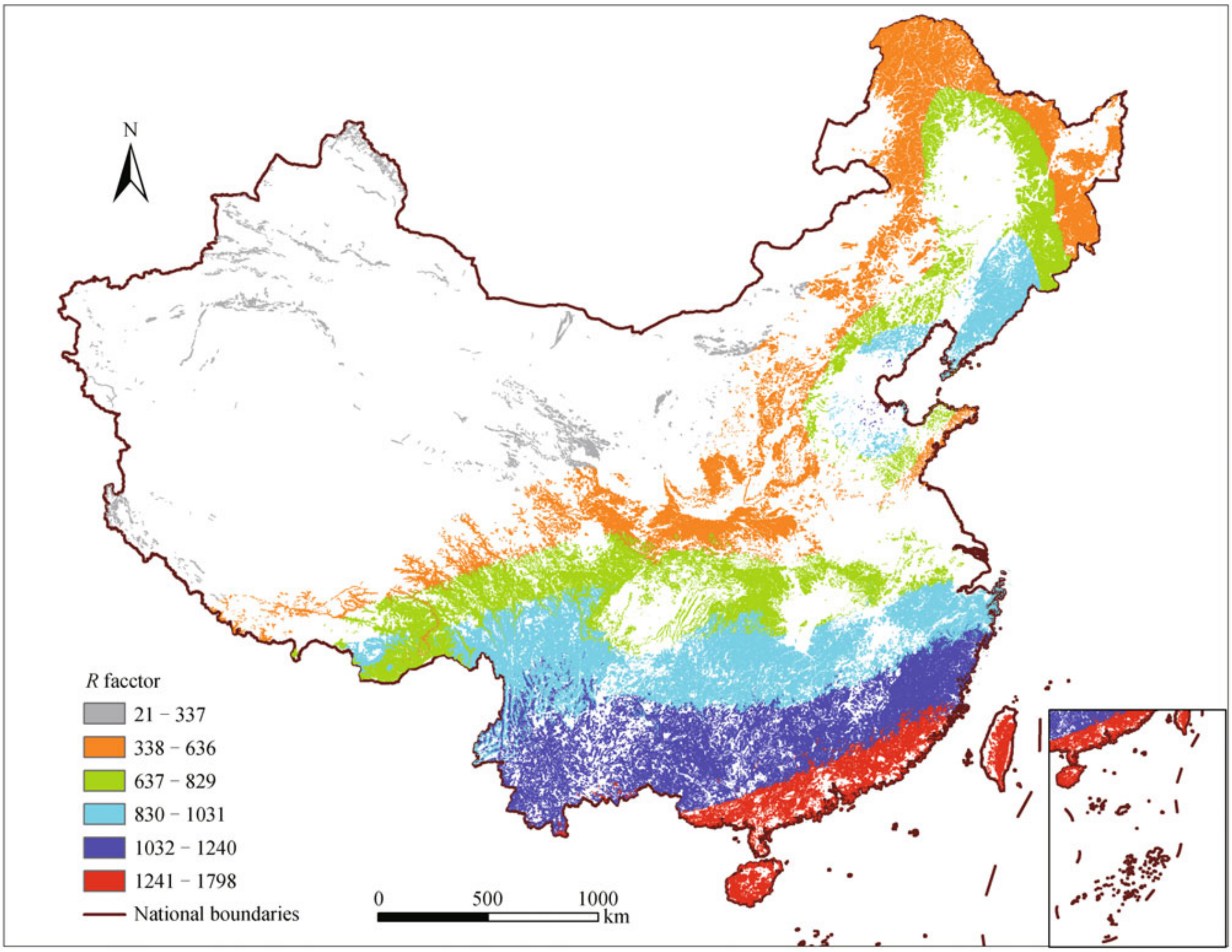

Fig. 3 Spatial distribution of rainfall factor (*R*)

litter layer, a type of ground cover, is taken into account in factor *C*. The *K* map and its distribution percentage are showed in Fig. 4 and Table 3.

3.3 Topographic factor (*LS*)

It was well known that the amount of erosion increases with the increase of slope length. The slope length is defined as the horizontal distance, along the flow path, from the origin of overland flow to the point where either the slope gradient decreases to a point at which deposition begins to occur, or runoff becomes concentrated in a defined channel according to Renard et al. (1997). The *L*- and *S*- factor jointly represent the influences of slope length, steepness, and shape on sediment production. USLE represents the integrated effects rill and inter-rill erosion. Rill erosion primarily induced by surface runoff increases in a downslope direction because the runoff increases in this direction. Inter-rill erosion primarily induced by raindrop impact is uniform along a slope. The *L*-factor is greater for those conditions where rill erosion tends to be greater compared to inter-rill erosion. Erosion increases with the slope steepness but, in contrast to the *L*-factor representing the effects of slope length, the USLE make no differentiation between rill and inter-rill erosion in the *S*-factor that estimates the effect of slope steepness on soil erosion.

In this study, the *LS*-factor was computed from the DEM using the equations such as Eq. (5) proposed by Moore and Burch (Moore and Burch, 1986). The flow accumulation was calculated from a DEM using watershed delineation techniques, and the slope steepness was computed from the DEM also. The equation is:

$$LS = (\text{Flow accumulation} \times \text{Cell size}/22.13)^{0.4} \times (\text{Sin slope}/0.0896)^{1.3}, \quad (5)$$

where Flow accumulation is the number of cells contributing to flow into a given cell and Cell size is the size of the cells being used in the grid based representation

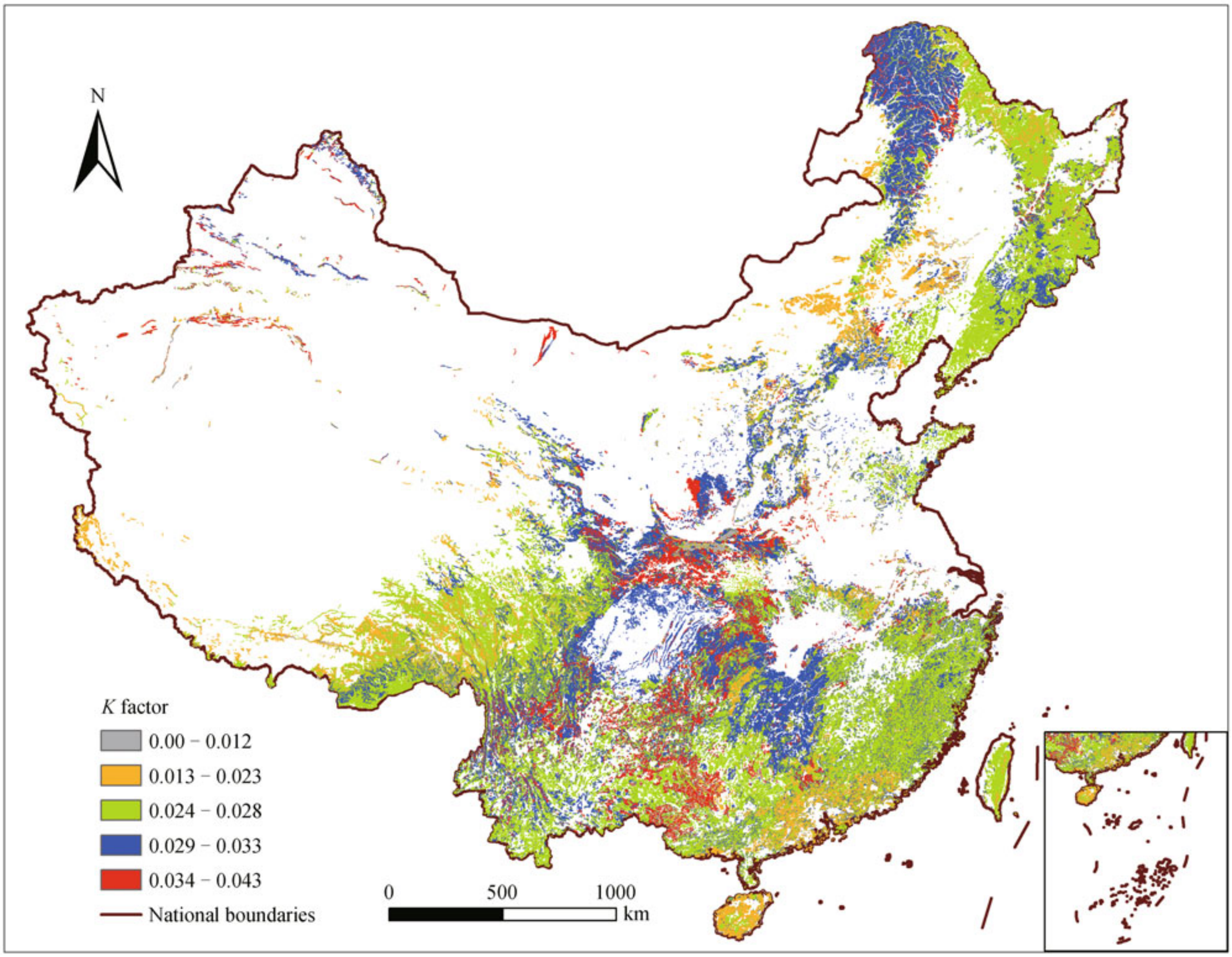

Fig. 4 Spatial distribution of soil erodibility factor (K)

of the landscape. Using Eq. (5), LS and its distribution were estimated, which are shown in Fig. 5 and Table 3.

3.4 Cover and management factor (C)

The C developed for agricultural crops and represented the effect of cropping and management practices in agricultural management, and the effect of ground, tree, and grass covers on reducing soil loss in non-agricultural situation, needs to be adapted to be applicable to forest cover types. As the vegetation cover increases, the soil loss decreases. While, forest cover types vary from tree species, ages, densities, and floor vegetations (Kitahara et al., 2000), and they regarded that factors C and P (discussed later) should be expressed either as a function of time or categorically for each year after the disturbance for mountainous forests. For example, a model may be created so that C is 1 when the ground cover totally disappears due to deforestation, construction of roads, timber yarding, landslides, or forest fires that burn all trees, the ground cover, and the soil; and the C value gradually decreases as the natural vegetation recovers. While, there are no detail national forest spatial characters data (e.g. natural forest or artificial forest, ages, densities, and floor vegetations and forest disturbances [harvest operations, landslides, or fire]) in China. In this study, we determined values for the factors C based on forest types and previous studies. The forest land has been classified into six land use classes, namely 1) coniferous forest land, 2) conifer-broadleaved mixed forest land, 3) broadleaved forest land, 4) bamboo forest land, 5) shrub forest land and 6) orchard forest land. Finally, C was assigned for different forests types using Table 2. The magnitude and the spatial distribution of forest management factor are given in Table 3 and Fig. 6.

3.5 Conservation practice factor (P)

P is the ratio of soil loss with a specific support practice to the corresponding loss with up and down slope cultivation (Wischmeier and Smith, 1978). The lower the P-value, the more effective the conservation practice is deemed to be at reducing soil erosion. If there are no support practices, the

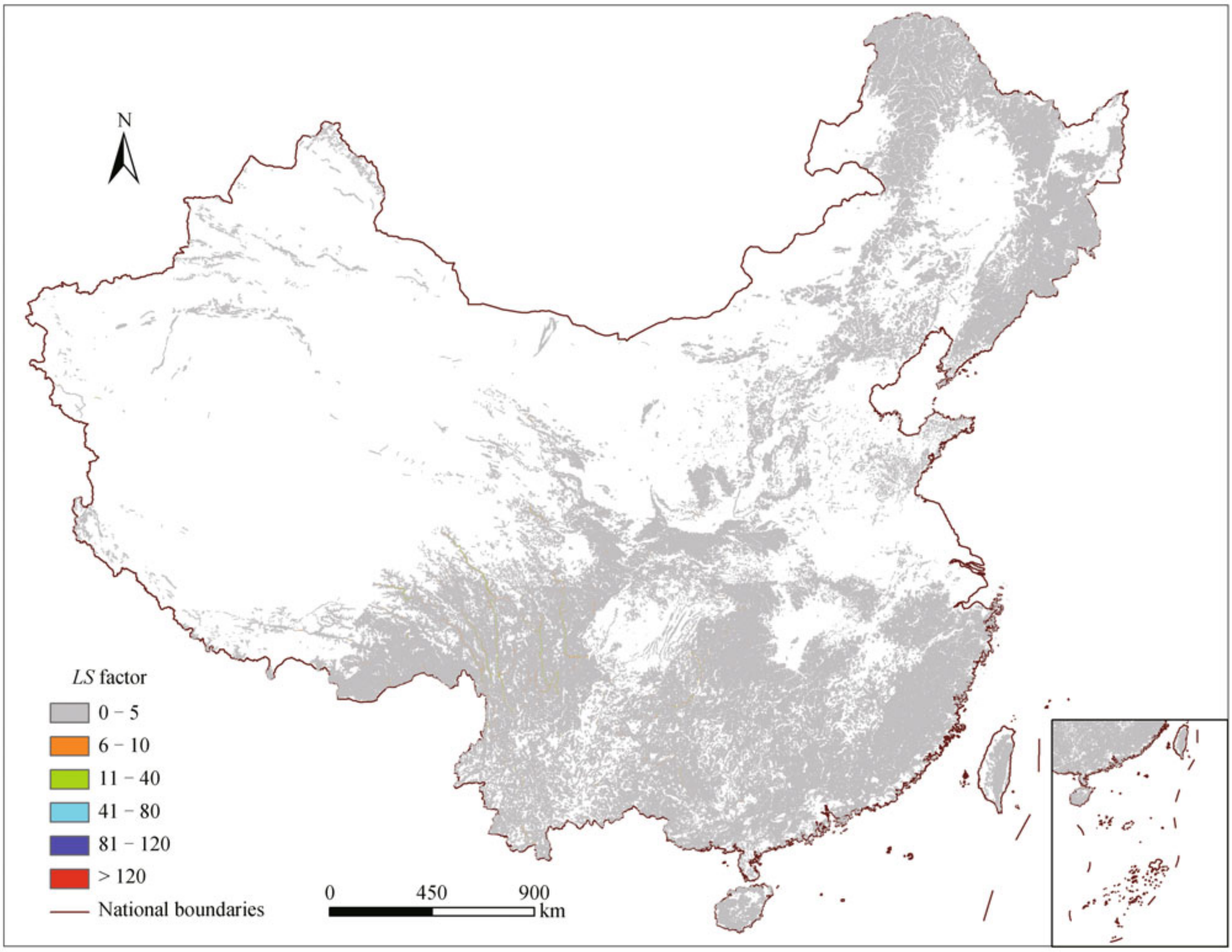

Fig. 5 Spatial distribution of topographic factor (*LS*)

P-factor is 1.0. Although some Chinese state key forestry ecological projects were carried out, few support practices were adopted in woodland, so in this study, the value of *P*-factor is 1.0.

4 Results and discussion

To determine the spatial distribution of average annual soil loss in Chinese woodland, cell-based USLE parameters were multiplied in the specified 100 m × 100 m cells. Average annual soil losses were grouped into seven scales as proposed by Singh et al. (1992) and Chinese soil erosion taxonomy. The spatial distribution of average annual soil loss rate is presented in Fig. 7. About 99.81% of Chinese woodland area was found out to be under very slight erosion class (Table 4). Areas covered by slight, moderate, high, very high, severe and very severe erosion potential zones are 0.09%, 0.04%, 0.02%, 0.01%, 0.01% and 0.00% respectively (Table 4). It indicated that forests had obvious function in water and soil conservation because the observation of the areas identified as high erosion potential zone, namely more than $5\ t \cdot ha^{-1} \cdot a^{-1}$ (Dabral et al., 2008), was only about 0.11% of the total forest area of the country.

The results of variances of soil loss and its distribution among soil erosion classes in woodlands were similar with many previous results in mountainous forest areas using USLE (Millward and Mersey, 1999; Shi et al., 2004; Sun and McNulty, 1998; Zhang et al., 2008), but the average annual soil loss under woodlands here was different with the results of land use systems estimated by USLE in hilly catchment (Huang et al., 1993; Shi et al., 2004; Wei et al., 2007; Dabral et al., 2008). This was mainly associated with studied land use ecosystems and human activities. First of all, the dense and multistory canopy of forest was thought to play a key role in reducing the terminal velocity of raindrops and the attendant soil erosion, and some scholars have found that soil erosion was negatively linearly correlated with the vegetation coverage in the hilly area (Gyssels et al., 2005; Zhou et al., 2006). Secondly, it was recognized that the dense forest litter and roots could reduce runoff and soil-water loss because the dense forest

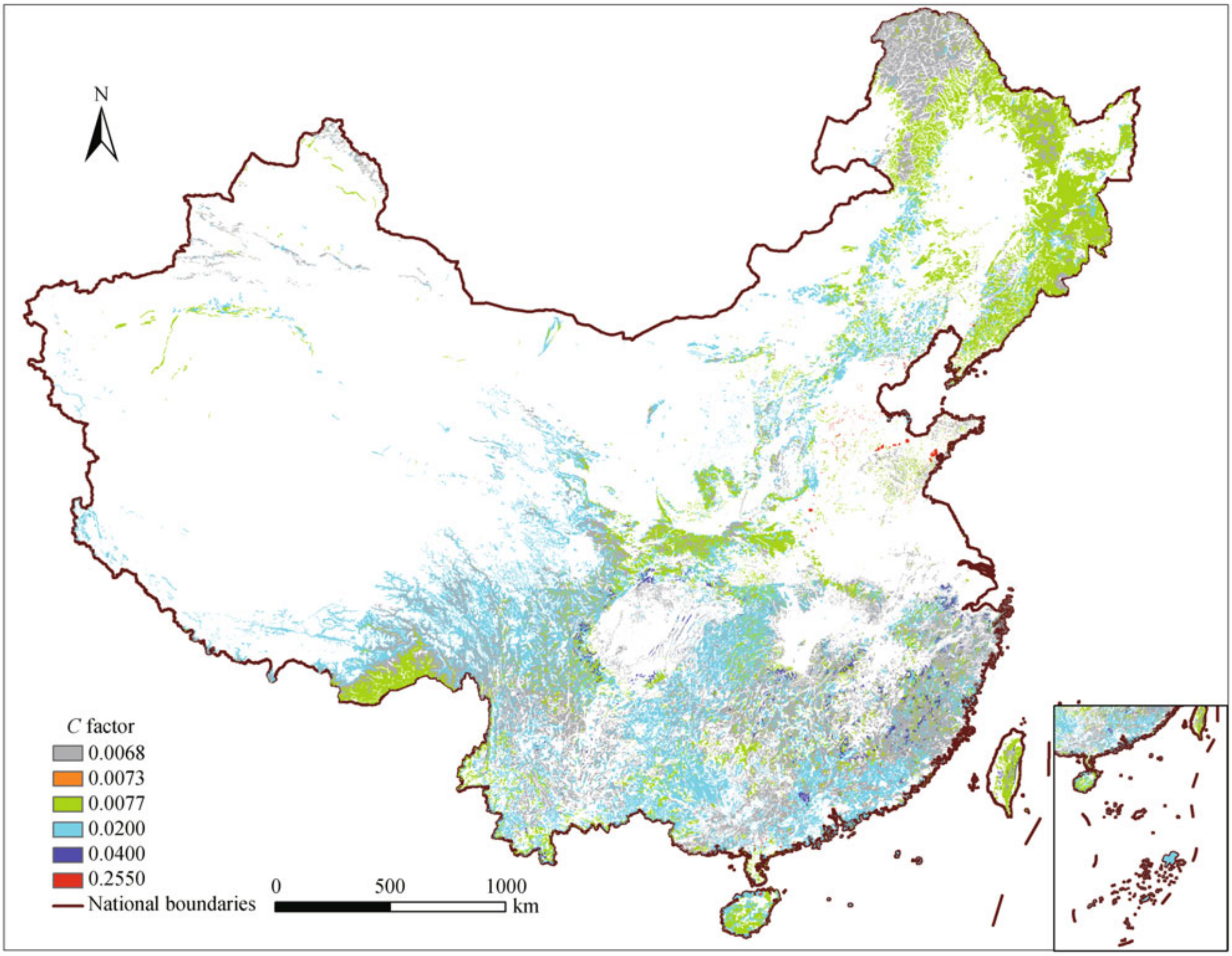

Fig. 6 Spatial distribution of cover and management factor (C)

Table 2 Cover and management factors C for different forests

Forest types	C value	Literature	Remark
Coniferous forest	0.0068		1)
Conifer-broadleaved mixed forest	0.0073	(Kitahara et al., 2000)	2)
Broadleaved forest	0.0077		3)
Bamboo forest	0.0400		4)
Shrub forest	0.0200	(Roose, 1977)	5)
Orchard forest	0.2550	(Dabral et al., 2008)	6)

Note: 1) Calculated from the C value of *Abies sachalinensis* (Sasa) (0.0086), *Pinus densiflora* 30-year-old (0.084), *Crypmmeria japonica* middle-aged (0.0049) and *Chamaecyparis obtusa* middle-aged (Sasa) (0.0050), 2) Calculated from the C value of mixed forest (0.016 and 0.0073), *Pinus densiflora* and Broad-leaved stand (0.0045) and *Larix leptolepis* and Broad-leaved stand (0.0014), 3) Calculated from the C value of *Fagus crenata* (0.0069), Broad leaved secondary forest (0.0085), 4) For artificial forests of bamboo, whose floor is not covered by grass for intensive management, the C values are about 0.04, 5) Calculated from the C value of grassland (0.02) which is cited from Roose(1977), 6) Calculated from the C value of Fellow agriculture (0.18) and Jhum cultivation (0.33) from Dabral et al. (2008)

litter combining with tall vegetation is to buffer raindrop impacts, increase surface roughness, and reduce soil splash and detachment (Descheemaeker et al., 2006; Blanco and Lal, 2008), and tree roots increase soil anti-scouribility, soil anti-shear strength and enhance soil water penetrability (Famiglietti et al., 1998; Mao et al., 2006; Wei et al., 2007). Lastly, human interferes play a key role in influencing the runoff and soil erosion (Poesen et al., 2001; Ruysschaert et al., 2005), and most Chinese forests are under extensive management,thus the intensity induced by human in

Table 3 Distribution percentage of factors

Factors and soil loss	Range	Area/km^2	Area/%
R/($MJ\cdot mm\cdot ha^{-1}\cdot h^{-1}\cdot a^{-1}$)	21–337	84692.38	3.47
	237–636	561733.16	22.99
	637–829	553138.32	22.64
	830–1031	589944.11	24.14
	1032–1240	487673.22	19.96
	1241–1798	166414.36	6.80
	Total[a)]	2443595.55	100.00
K/($t\cdot ha\cdot h\cdot ha^{-1}\cdot MJ^{-1}\cdot mm^{-1}$)	0.008–0.012	33337.66	1.36
	0.013–0.023	296393.48	12.09
	0.024–0.028	1182452.02	48.22
	0.029–0.033	701119.51	28.59
	0.034–0.043	238871.21	9.74
	Total[a)]	2452173.88	100.00
LS (unitless)	0–5	2444793.14	99.68
	6–10	3892.10	0.16
	11–40	2954.11	0.12
	41–80	532.61	0.02
	81–120	196.57	0.01
	>120	346.99	0.01
	Total[a)]	2452715.52	100.00
C (unitless)	0.0068	804545.2	32.54
	0.0073	21959.96	0.89
	0.0077	683614.99	27.65
	0.0200	923647.66	37.36
	0.0400	32939.26	1.33
	0.255	5435.61	0.22
	Total[a)]	2472142.68	100.00

Note: a) Total area is different because of the different collected data and its changing of cell resolution

Chinese wood land was little. All those made undisturbed perennial woodland areas have best function in reducing the amount of runoff and soil erosion among all land use systems (Blanco and Lal, 2008). Unlike other scholars, we here only study the soil erosion under woodland areas without taking human activities into account because of scarcity of forest management and conservation practice data at the national scale. But fortunately, most of Chinese forests are under extensive management. Thus the results here are reasonable to some extent.

The percentage of soil loss induced by slight erosion and slight erosion were decreased with the increase of slope degree under woodlands, they were decreasing from approximately 64.26% and 18.47% under 0–5 degree areas to 2.63% and 5.68% under >45 degree areas, respectively, and they were respectively less than 50% and 17% when the slope was above 15–25 degree (Fig. 7). Whereas the percentages of soil loss induced by serve and vary server erosion varying from about 0.67% and 0.00% under 0–5 degree woodlands to about 16.81% and 48.94% under >45 degree woodlands, respectively. The highest soil erosion mostly occurred in where slope length and steepness factor were biggest (Figs. 6 and 7). This indicated that they have already suffered server and very server erosion due to undulating topography, this was consistent with the results achieved by Dabral et al. (2008). It is well known that topography plays a critical role in controlling water and soil conservation, and some relationships between soil loss and slope angle were achieved by many scholars (Kitahara et al., 2000; Wang and Jiao, 1996). Although about 0.11% of woodland area is having average annual soil loss rate more than 5 t ha^{-1} a^{-1}, while it results in about 58.03% of total woodlands soil loss (Table 4). Therefore, those woodland areas are required to be treated.

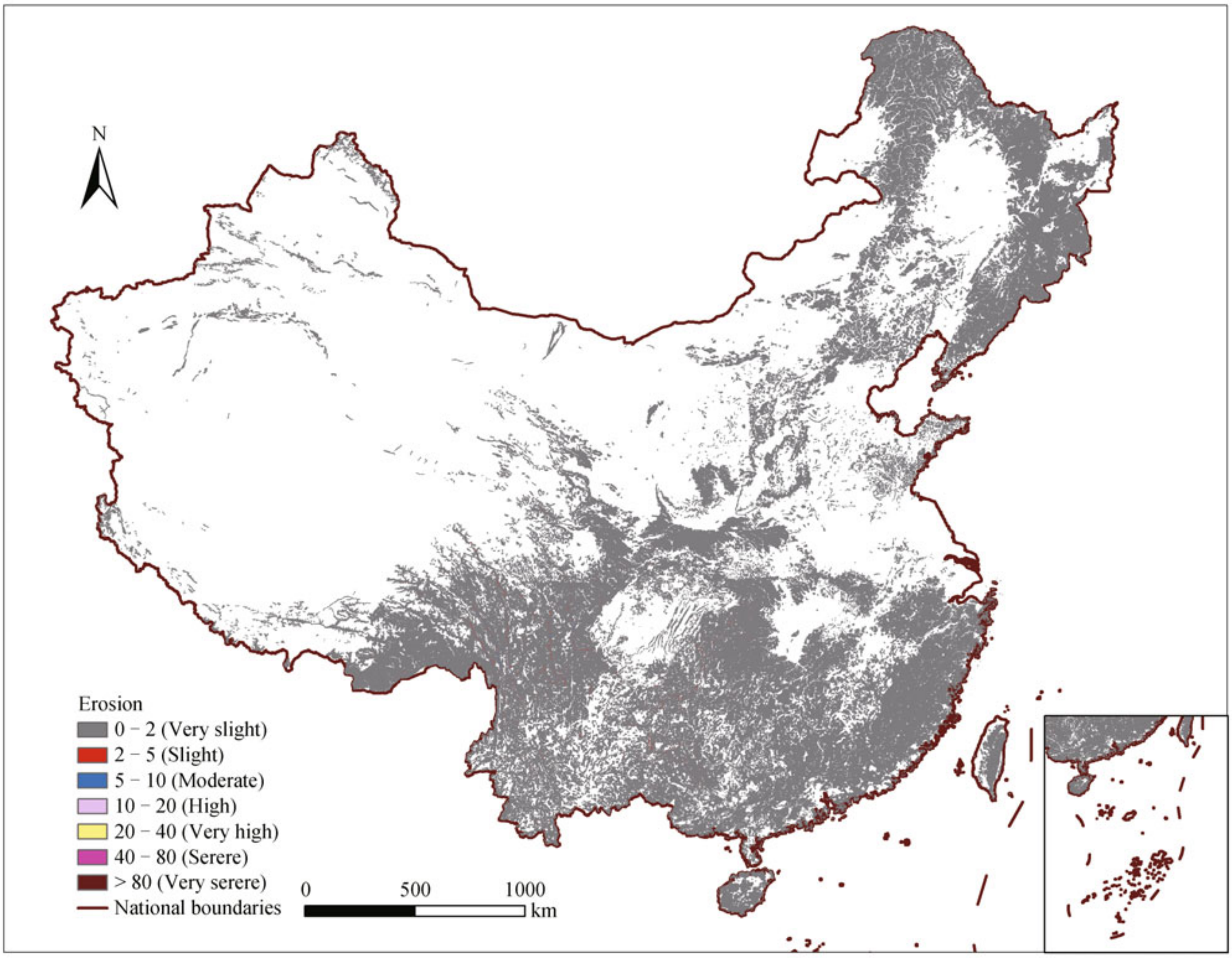

Fig. 7 Spatial distribution of annual soil loss in Chinese woodland

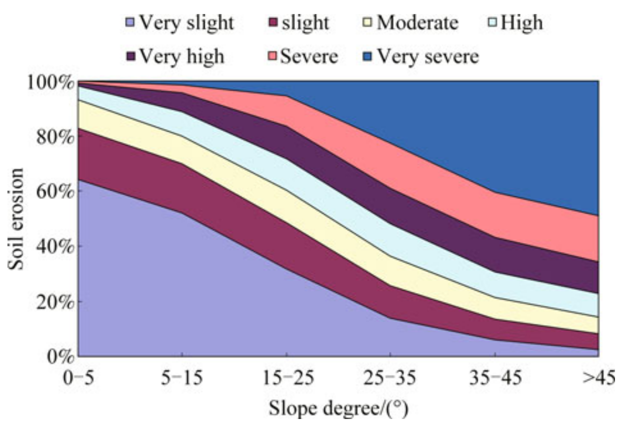

Fig. 8 Soil loss (%) of different soil erosion classes to slope degree

5 Conclusions

A quantitative assessment of average annual soil loss on grid basis was made with a view to know the function of forest in reducing soil erosion and the feasibility of application of the well-known USLE to Chinese mountainous woodlands. The use of spatial database including precipitation, topography, and soil and woodland data enabled the determination of the spatial distribution of the USLE parameters. The average annual soil erosion for Chinese woodlands was found to be $3.82\,t \cdot km^{-2} \cdot a^{-1}$. About 99.81% of the woodland area is found out to be under very slight erosion class. Areas covered by slight, moderate, high, very high, severe and very severe erosion potential zones are 0.09%, 0.04%, 0.02%, 0.01%, 0.01% and 0.00% respectively, while approximately 58.03% of soil loss under Chinese woodlands occur under high erosion potential zones, namely more than $5\,t \cdot ha^{-1} \cdot a^{-1}$. Those results are consistent with many previous researches in mountainous forests or hilly catchments. Thus the USLE can be widely applied to forest regions throughout China. Future studies are required to consider forest litter and silvicultural treatments in assessing spatial and temporal distributions of the woodland soil loss using USLE at the national scale.

Table 4 Distribution percentage of soil loss

Soil loss rate/($t \cdot ha^{-1} \cdot a^{-1}$)	Area/km^2	Area/%	Soil erosion class	Soil loss/($t \cdot a^{-1}$)	Soil loss/%
0–2	2433470.07	99.81	Very slight	2624088.73	28.15
2–5	2289.08	0.09	Slight	1289029.18	13.83
5–10	1040.86	0.04	Moderate	944721.73	10.13
10–20	593.67	0.02	High	947255.36	10.16
20–40	333.58	0.01	Very high	992086.72	10.64
40–80	181.34	0.01	Severe	1040582.74	11.16
>80	114.63	0.00	Very severe	1485367.32	15.93
Total	2438023.23	100.00		9323131.78	100

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