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Development of GIS-based FUSLE model in a Chinese fir forest sub-catchment with a focus on the litter in the Dabie Mountains, China

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Abstract

Land use plays an important role in soil loss and other environmental problems. Correct prediction of soil loss from different types of land use is very important to land use policy making in the Dabie Mountains, China. Field observations of water and soil loss were carried out in the Shangshe catchment in four types of land use in 1999–2002. This paper reports the study of soil loss in the sub-catchment of Chinese fir forest.

Field observations of water and soil loss were carried out at micro-plot scale, Universal Soil Loss Equation (USLE)-plot scale and the sub-catchment scale in the sub-catchment of Chinese fir forest. Analysis of these field observation data shows that litter in forest has important hydrological function. In the Chinese fir forest, the micro-plot without litter and grass produced 71 times soil loss of that from a micro-plot with litter and grass at the same gradient in 2000.

By integrating a linear regression method with GIS and USLE, an USLE in forest with a focus on litter (FUSLE) model was developed to predict soil loss in forest. Rain erosivity factor is turned into modified rain erosivity factor when litter is added as a new factor. These measures are believed more practical in soil loss prediction in forest because the litter factor shows the real scenario of soil loss in the forest. Further more, the meter scale plot method is able to get enough field observation data in a few years for soil loss prediction and it is less expensive.

Keywords: GIS; Soil loss; FUSLE; Litter; Chinese fir forest

1. Introduction

Soil erosion has increased throughout the 20th century in watershed of the Yangtze River, China (Zhang et al., 1999). It has caused sedimentation in dams and riverbeds, which in turn intensified flooding. Much effort has been made to understand the mechanism of soil erosion and predict soil loss. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965) was an empirical model for predicting the average annual soil loss caused by rainfall. With this model, soil loss is evaluated by extrapolating from plot and sub-catchments to catchments. Attempts have been made to use it on forest land (Wischmeier and Smith, 1978; Lufafa et al., 2003) and pasture (Bacchi et al., 2003). However, in dense forest ecosystems, canopy coverage is very high. For single events in an evergreen forest, coverage does not vary much among seasons. More over, usually the forest floor is covered with litter and grass, which has a good buffering effect on overland flows, because litter has a great detention and retention capacity (Balcı, 1963; Wu and Wang, 1993). So this approach has the substantial obstacle of spatial heterogeneity in the forest catchment, and more methods need to be tried for soil loss prediction in forest.

Accurate estimation of soil erosion due to water is very important in several environmental contexts, such as the assessment of potential soil loss from forests and the evaluation of the loss of water storage capacity in reservoirs due to sediment deposition. To know the response of watersheds and sub-systems, quantification of their hydrological and erosion

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behavior is needed. In the Shangshe catchment, there are mainly five kinds of land use: paddy field, cultivated land, pine (*Pinus massoniana* L.) forest, Chinese fir (*Cunninghamia lanceolata* L.) forest and tea (*Camallia sinensis* L.) garden. In the Shangshe catchment, four sub-catchments of different land types were selected as experiment sites (Zhuang et al., 2004). Four 45° sharp-crested V-notch weirs were set up in the catchments of pine forest (0.86 ha), Chinese fir forest (0.89 ha), cultivated land (0.74 ha) and tea garden (0.59 ha), respectively. This study was carried out in the sub-catchment of Chinese fir forest.

Soil erosion monitoring can be conducted on-site (at plot level) and off-site (at sub-catchment and catchment levels). Both of these two monitoring approaches have advantages and disadvantages (Herlina et al., 2003). Sub-catchment or catchment levels approach can better describe the rainfall-runoff response in a catchment scale and response to certain management practices. Upslope or on-site monitoring, on the other hand, is relatively simple to conduct and inexpensive. This type of monitoring is best suited to portraying soil erosion processes and soil disturbances on-site (Corner et al., 1996). Comparison of simulated erosion patterns with observed erosion patterns is necessary to confirm a model's robustness, not only at the soil erosion monitoring off-site, but also on-site soil erosion. Analysis of the soil erosion monitoring off-site and on-site soil erosion will show their mutual relationship. Because of these considerations, both the on-site and off-site soil erosion-monitoring methods were used.

1.1. Study area

This study was conducted in the Shangshe catchment (34°32′20″N, 116°50′12″E) of the Dabie Mountains in Yuexi prefecture of Anhui Province, China. Details of the Shangshe catchment were reported by Zhuang et al. (2004). In the Shangshe catchment, a sub-catchment of Chinese fir plantation forest of 8900 m^2 was selected for field observations (Fig. 1). The average height of trees is 6.1 m and the $\bar{D}_{1.3}$ (average diameter of trees at the 1.3 m height) is 8.1 cm. The tree density is 1660 trees ha^{-1}. Under the forest, there were grasses, shrubs and litter.

This study investigated soil loss at micro-plot level, USLE-plot level, and sub-catchment level, with the following objectives: (1) to develop an empirical soil loss model suitable for predicting soil loss from single rainfall-runoff events in the forest and (2) to investigate the extent to which on-site monitoring of soil losses agree with the results off-site monitoring of sediment yields in the forest.

2. Materials and methods

2.1. Field observation in the sub-catchment scale

A 45° V-notch sharp-crested weir, equipped with a float-type water level recorder, was built at the outlet of the sub-catchment of Chinese fir forest (Fig. 1). At 8 a.m., the recorder paper of a water gauge was changed manually; the water level at the weir was measured for use in correcting the error of the water level in the recorder paper. Details of water runoff and suspended sediment concentration observations, as well as runoff and suspended sediment discharge calculations in the sub-catchment scale can be referred from Zhang et al. (2004). The sediment at the weir was measured every 3 months and then distributed to each event according to its ratio of suspended sediment discharge in each season. The sediment discharge (SD, t) was transformed into specific sediment discharge (SSD, t km^{-2}). Field observation data of SSD for single events in 2000 were used in this study.

2.2. Precipitation observation

A manual rain gauge and an autographic rain gauge were set up to survey precipitation and rainfall intensity 400 m away from the weir at the monitored site of Chinese fir forest. The recorder paper of the autographic rain gauge was changed at 8 a.m. For every rainfall event, precipitation was read from the recorder paper for the automatic rain gauge and compared with data from the manual rain gauge. Field observation data of precipitation in 1999–2002 were used in this study.

2.3. Field observation in the USLE-plot and micro-plot scale

The method of micro-plot at a meter scale was applied in the sub-catchment of Chinese fir forest in 2000. Nine micro-plots of 2 m × 1 m on slopes of 3°, 6°, 8°, 11°, 15°, 25°, 28°, 33° and

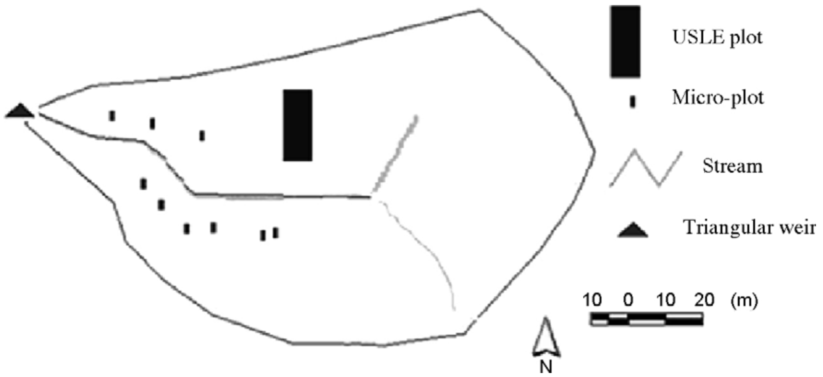

Fig. 1. Sub-catchment of Chinese fir forest and the USLE-plot, micro-plots and the triangular weir in it.

Fig. 2. A USLE-plot in a Chinese fir forest.

35° were set up, whereas an USLE-plot of 22.1 m × 5 m was on a slope of 27.9° in the sub-catchment of Chinese fir forest (Fig. 2). The micro-plots of 3°, 6°, 8°, 11° and 15° were covered with natural litter and grass, while the litter and grass on the other four micro-plots were removed. For each micro-plot, one container was used to collect water and sediment discharge, whereas for the USLE-plot, volume of surface runoff was calculated by measuring the height of the water in the first and second collecting tanks. A 200–500 ml sample was taken to the laboratory where the sediment was filtered, dried in an oven at 110 °C and weighed. For each rainfall-runoff event, the runoff volume and soil sediment loss from the micro-plots and the USLE-plot were calculated. SD (t) was transformed into SSD ($\mathrm{t\,km^{-2}}$). Field observation data of USLE-plot in 2000, 2001 and 2002 were used in this study.

2.4. FUSLE model for soil loss prediction

The USLE has been applied widely at a watershed scale on the basis of a lumped approach (Williams and Berndt, 1972, 1977; Wilson, 1986; Griffin et al., 1988; Dickinson and Collins, 1998). GIS development, which reduces the time of analyses, has facilitated the application of USLE with a spatially distributed approach (Kinnell, 2001). However, the forest is a complete different ecosystem from the cultivated land. Canopy cover, sapling density, litter depth and woody debris appeared to be important ecological factors that determine the magnitude of soil loss (Herlina et al., 2003). Trees provide and maintain a litter layer which protects the soil against the impact of raindrops (Binkley and Brown, 1993). Wang and Xie (1998) reported that soil cover removal often increases erosion by 10–100 times, while tree canopy removal without distributing soil cover increases soil erosion rate by less than 50% (Wang and Xie, 1998; Herlina et al., 2003). The protective values of stands lie in both the ability of the canopy to decrease the power of raindrops and their ability to provide materials for soil cover on the forest floor. As a result, energy of raindrops, depending on their drop size, and velocity, is reduced to almost zero when they reach the soil (Binkley and Brown, 1993). Because of the power function of litter on soil loss control in forest, the litter is added as a factor into the USLE model, thereby creating an FUSLE model (USLE in forest with a focus on litter), as in Eq. (1):

$$Y = R_{\mathrm{e}}\,C\,L\,S\,P\,K\,l_t \tag{1}$$

where Y is the SSD ($\mathrm{t\,km^{-2}}$ or $\mathrm{g\,m^{-2}}$); R_{e} the modified rain erosivity factor, is the number of effective rainfall erosion index unit for a specified soil as measured on a unit plot, which is defined as a 22.1 m length of uniform 9% slope ($\mathrm{J\,mm\,m^{-2}\,h^{1}}$); C the cover and management factor, is the ratio of soil loss form an area with specified cover and management to that from an identical area in tilled continuous fallow; K the soil erodibility factor, is the soil loss rate per erosion index unit for a specified soil as measured on a unit plot, which is defined as a 22.1 m length of uniform 9% slope continuously in clean-tilled fallow ($\mathrm{g\,h\,J^{-1}\,mm^{-1}}$); L the soil erodibility factor, is the ratio of soil loss from the field slope gradient to that form a 9% slope under identical conditions; S the slope-steepness factor, is the ratio of soil loss from the field slope gradient to that form a 9% slope under otherwise identical conditions; P the support practice factor, is the ratio of soil loss with a support practice liking contouring, strip-cropping, or terracing to that with straight-row farming up and down the slope (in the Chinese fir plantation forest, because there is no such support practice, P is considered as 1 in this study); l_t is the litter factor, is the ratio of soil loss form a forest land with specified litter on the ground to that from an identical area without litter.

3. Factors in FUSLE model

3.1. R_e factor

Yang and Guo (1994), based on observed data from normal runoff plots in cultivated land, analyzed the relationship between the R values calculated at different intervals (5 min to 1 h) and the amount of soil loss for every event. They reported that the soil loss in the USLE-plot scale was closely correlated with R value calculated at 10-min intervals in northern China. This method is applied in this study. The equation for R is (Wischmeier and Smith, 1965)

$$R = \sum_{i}^{n} E_i I_{30} \tag{2}$$

where R is the rainfall-runoff erosivity factor by precipitation ($\mathrm{J\,mm\,m^{-2}\,h^{-1}}$), E_i the rain energy in one storm in the i 10-min intervals and I_{30} is the maximum continuous rain intensity in a 30 min period in a storm ($\mathrm{mm\,h^{-1}}$). In China, the R factor is decreased to one hundredth in application.

The Committee of the Yellow River of China has also computed a regression equation that incorporates rain energy and intensity (Zhang and Hu, 1996):

$$E = 210.3 + 89\log_{10} I \tag{3}$$

where E is the rain energy in one period ($\mathrm{J\,m^{-2}\,cm^{-1}}$) and I is the rain intensity ($\mathrm{cm\,h^{-1}}$).

This regression equation was applied to calculate E in this study.

In general, the erosion models have difficulties predicting small-scale events that are caused by the large natural variation of factors related to soil loss data (Neering, 1998). For many small rainfall events, there is no runoff at all; for most rainfall-runoff events, rain loss varies greatly. Using R factor without considering the variance of rain loss will over-predict soil loss for small-scale events. There for, modified effective rainfall erosivity was proposed to smooth the error of rain loss on soil loss in the USLE application in China. It is calculated with Eq. (4):

$$R_e = R - R_l \tag{4}$$

where R_e is the modified R factor (J mm m^{-2} h^{-1}), R the rain erosivity factor (J mm m^{-2} h^{-1}) and R_l is the loss of R factor till the occurrence of rainfall-runoff (J mm m^{-2} h^{-1}).

In 1999 and 2000 in the Shangshe catchment 28 and 18 rainfall-runoff events happened in the sub-catchments of Chinese fir. Because the runoff observation was carried out at the sub-catchment of Chinese fir, by comparing the hydrograph of runoff with the hyetograph of precipitation, the loss of rainfall can be determined. Eq. (5) was applied to calculate the R_e in this study:

$$R_e = (E - E_l)I_{30} \tag{5}$$

where R_e is the modified R factor (J mm m^{-2} h^{-1}), E the rain energy of one rainfall-runoff event (J m^{-2}) and E_l the rain loss of energy till the occurrence of rainfall-runoff in the same rainfall-runoff event (J m^{-2}) is determined by comparing the hydrograph of runoff with the hyetograph of precipitation.

For the 46 rainfall runoff events in 1999 and 2000, the values of R_e were calculated. R_e was linearly related to rainfall in the Chinese fir forest (Fig. 3). A linear regression equation of R_e with the precipitation was determined (Eq. (6)):

$$R_e = 5.65x - 14.5 \tag{6}$$

where x represents the rainfall (mm) for single events.

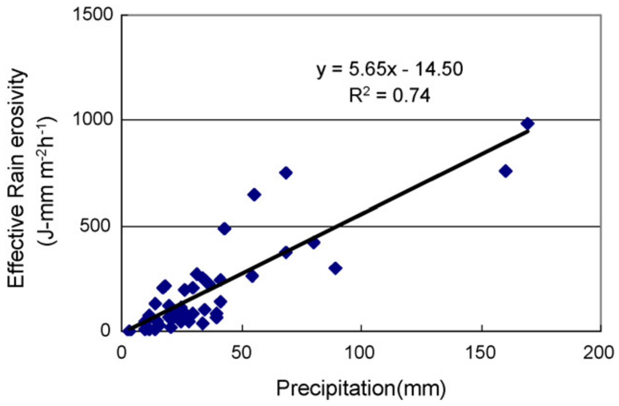

Fig. 3. Relationship between rainfall and R_e in Chinese fir forest.

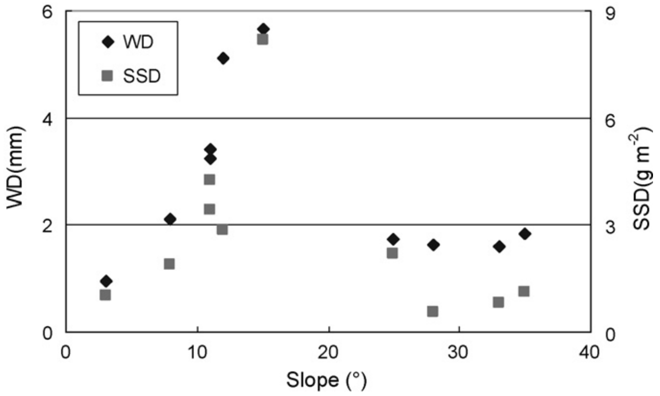

Fig. 4. Relationship among WD, SSD and slope at micro-plot scale on 16 August 2000.

3.2. L and S factors

3.2.1. Effect of slope on soil loss in the micro-plot scale

Analyses of field observation data of 15 rainfall-runoff events in 2000 in the micro-plot scale showed that water discharge (WD, mm) and SSD increased with the slope, despite the fact that the relationship between slopes and SSD in the micro-plot scale varied among events. The 16 August 2000 event was shown as an example (Fig. 4). The values of SSD in the micro-plots with slope of 25°, 28°, 33° and 35° were extremely low. This was because the function of litter and grass on the forest floor and it will be discussed below.

3.2.2. LS factors in the sub-catchment scale

The slope was derived from the digital elevation model (DEM) of the sub-catchment of Chinese fir forest at the 1 m × 1 m grid size (Fig. 5). In both of the USLE and RUSLE (Revised USLE, Renard et al., 1997) models, slope length is defined as the horizontal distance from the origin of overland flow to the point where either the slope gradient decreases to a point at which deposition begins, or runoff becomes concentrated in a defined channel. In the present study, the L factor was determined with the following method. First, the flow path was determined under the hydro model under Arc-view for the Chinese fir forest sub-catchment. Then, the sub-catchment of Chinese fir forest was divided into three parts along a main stream and two sub-streams (Fig. 1). The slope lengths in the three parts are the ratios of their areas to the length of stream in them.

The LS factor was calculated according to Eq. (7) (Moore and Burch, 1986); it is shown in Fig. 6:

$$LS = \left(\frac{\lambda}{22.1}\right)^{0.6}\left(\frac{\sin\theta}{0.0896}\right)^{1.3} \tag{7}$$

In that equation LS is a unitless terrain factor, λ the length of slope in m and θ is the slope in degrees.

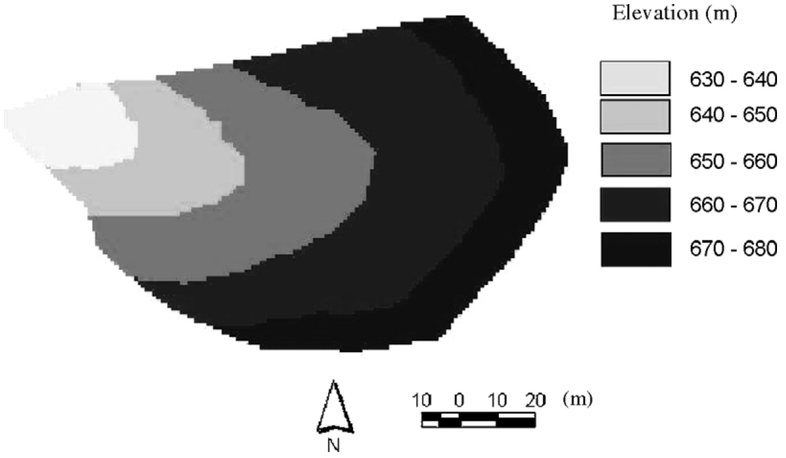

Fig. 5. DEM of the sub-catchment of Chinese fir forest.

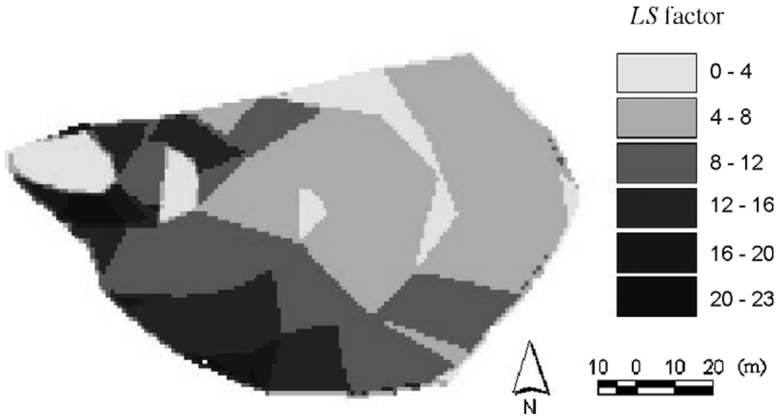

Fig. 6. *LS* factor in the sub-catchment of Chinese fir forest.

3.3. *K* factor

K is calculated with Eq. (8) (Williams et al., 1984):

$$K = \{0.2 + \mathrm{e}^{[-0.0256 S_1 (1 - S_1/100)]}\}\left[\frac{S_2}{(S_3 + S_2)}\right]^{0.3} \left\{\frac{1 - 0.25C}{[C + \mathrm{e}^{(3.72 - 2.95C)}]}\right\}\left\{\frac{1 - 0.7n}{[n + \mathrm{e}^{(-5.51 + 22.95n)}]}\right\} \quad (8)$$

where S_1 is the percentage of sand grain, S_2 the percentage of silt, S_3 the percentage of clay, C the percentage of organic matter, and $n = 1 - S_1/100$.

3.4. *C* factor

The vegetation cover and management factor (*C*) in the USLE has been studied extensively and used widely in the USA. In one type of land use, it is presumed that values of SSD at micro-plots show linear regression relationship with R_eLSPK. The constant parameter of linear regression model between SSD and R_eLSPK is considered as *C*. *P* factor in the forest is considered as 1.0. This method is used to determine the *C* factor in this study.

Field observation data of 15 rainfall runoff events at micro-plot scale were used for parameter estimates of linear regression. The SSD at the micro-plot scale without litter shed a linear relationship with R_eLSPK (Fig. 7). In Chinese fir forest *C* equals to 0.0827.

3.5. Litter factor

Trees provide and maintain a litter layer which protects the soil against the impact of raindrops (Binkley and Brown, 1993). Litter decomposition is vital to nutrient cycling and the productivity of forests (Didham, 1998) and is an important

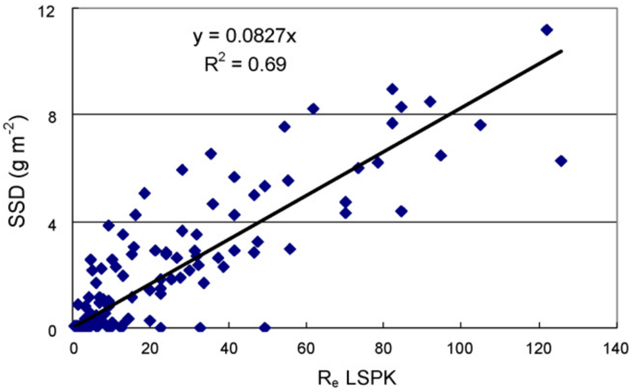

Fig. 7. Linear regression of SSD with R_eLSPK.

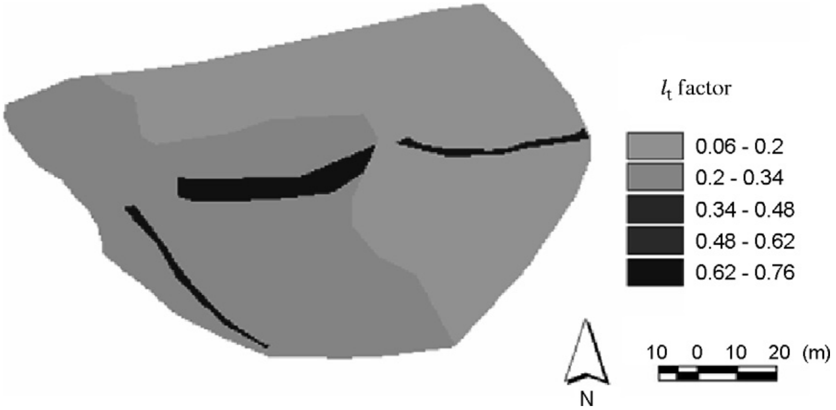

Fig. 8. Spatial distribution of litter factor.

component of the global budget (Aerts, 1997). On the other hand, the hydrological function of leaf litter layer is powerful. The tree canopy determines the size and erosive power of the raindrops. Sapling, grass, litter layer, and woody debris protected soil surface, thus preventing soil detachment, and provided surface roughness that minimized soil particle movement down the slope (Wang and Xie, 1998; Herlina et al., 2003). The effect of litter on soil erosion control was reported in the 1930s (Lowdermilk, 1930; Corter, 1938). In China, this work began from the 1960s. Especially in recent 20 years, hydrological effect of litter had been reported in most forest types all over China. Tan and Zhang (1995) reported that the water holding capacity of litter in the Chinese fir and maple (*Liquidambar formosana* H.) forest of the down reach of the Wu River was about 3 mm. Similarly, Yu et al. (2002) reported that the effective maximum water holding capacity of litter and moss in *Abies fabric* forests could reach 3.23 mm. The water regulating function of litter and moss will increase with the *Abies fabric* forest succession. Rao and Bi (2005) concluded that the effective maximum water holding capacity of forest litter in the Simian Mountain in Sichuan Province was between 1.8 and 4.6 mm. It is well accepted that roots stop rill development while the litter layer, limits splash erosion.

Plots with litter produced much lower SSD than the plots without litter (Fig. 4). The other rainfall events in 2000 showed similar results. This means that small areas without litter within catchments can be responsible for most of the runoff production, which has also implications for sediment delivery. Soil loss in a forest catchment should be the total of soil loss from areas with litter and without litter. There for in a catchment scale or sub-catchment scale, the litter coverage should also be included in the litter factor to predict soil loss. Eq. (9) is used to calculate the litter factor:

$$l_t = L_i \times \mathrm{Cov}_{Li} + 1 - \mathrm{Cov}_{Li} \qquad (9)$$

where l_t is the litter factor; L_i the ratio of annual SD in micro-plot with litter to SD in micro-plot of the same gradient without litter, here it is 0.014; Cov_{Li} is the coverage of litter in the sub-catchment. $L_i \times \mathrm{Cov}_{Li}$ means the coefficient of SSD from the area in a sub-catchment with litter, and $1 - \mathrm{Cov}_{Li}$ means the coefficient of SSD from the other area in the sub-catchment without litter.

Field observation of spatial distribution of litter coverage was carried out in March 2000 year in the sub-catchment of Chinese fir forest. Using Eq. (9), spatial distribution of litter factor was calculated and shown in Fig. 8. In Fig. 8, the area where the values of litter factor are between 0.62 and 0.76 is the road and places without litter, grass and shrub on the ground.

4. Result

With the map layer of *LS* (Fig. 6) and other factors introduced above, the temporal and spatial soil loss for 15 events in 2000 were calculated with Eq. (1). Predicted values of SSD in the sub-catchment scale with the FUSLE model for single events were compared with the observed values of SSD at the monitoring site of the sub-catchment outlet (Fig. 9). Their R^2 is 0.73. Spatial distribution of predicted annual soil loss in 2000 was transformed into a graph (Fig. 10). The values varied between 0 and 690 (t km^{-2}) in the sub-catchment of Chinese fir forest. The results are similar with the results in the sub-catchment of pine forest, and tea garden (two studies in the Shangshe catchment, unpublished). Predicted values of annual SSD in the USLE-plot scale with the FUSLE model in the 3 years of 2000, 2001 and 2002 agreed well with the observed values of annual SSD (Fig. 11). Annual values of SSD of 2000,

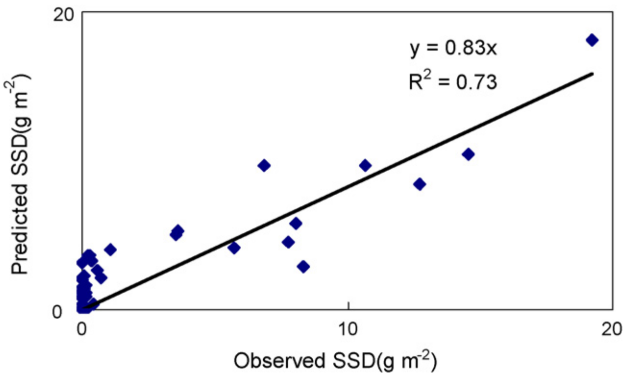

Fig. 9. Comparison between observed values of SSD for single events and predicted ones at sub-catchment scale in 1999 and 2000.

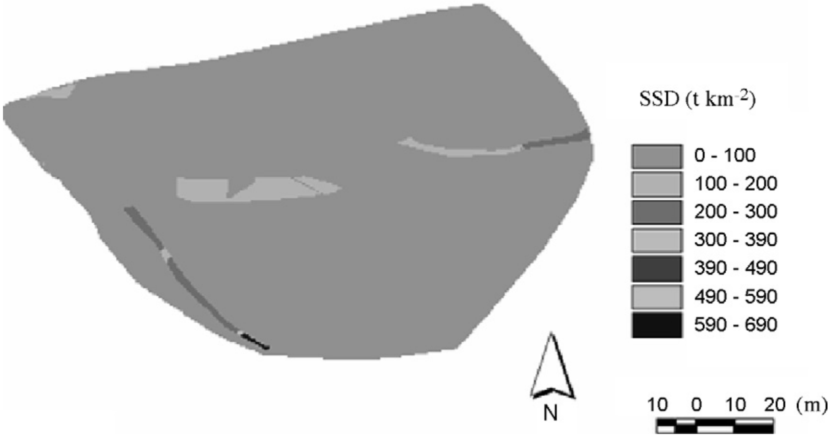

Fig. 10. Spatial distribution of predicted annual soil loss in 2000.

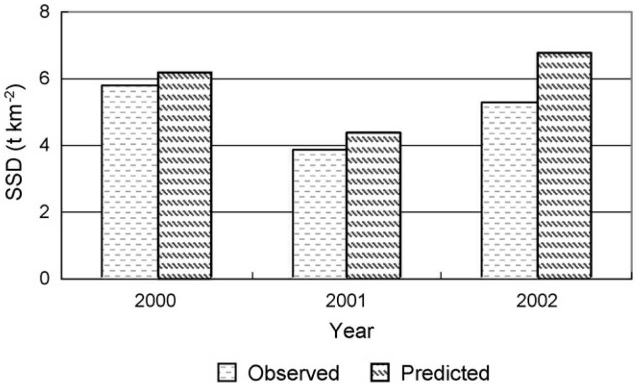

Fig. 11. Comparison between observed values of annual SSD in USLE-plot scale with predicted ones in 2000, 2001 and 2002.

2001 and 2002 in USLE-plot scale varied from 4 to 6.5 t km^2. They were very low because of the high coverage of litter and shrub in the USLE-plot.

5. Conclusions

In this study, field observations of water and sediment discharge were carried out in the micro-plot scale, USLE-plot scale and sub-catchment scale in the sub-catchment of Chinese fir forest in the Shangshe catchment, Dabie Mountains, China. Through analyses of field observation data in Chinese fir sub-catchment in 2000, 2001 and 2002, the following conclusions were reached:

Litter provides important hydrological function in forest. In the Chinese fir forest, the micro-plot without litter and grass produced 71 times soil loss of that from a micro-plot with litter and grass at the same gradient in 2000.

By integrating a linear regression method with USLE and GIS, an FUSLE model was developed to predict soil loss in forest. R factor was turned into R_e factor and the litter was added as a new factor. These measures were more practical in soil loss prediction in forest because the litter factor showed the real scenario of soil loss in the forest. Unlike USLE and RUSLE model, which need soil loss data in a long period to predict average annual soil loss, FUSLE model can be utilized with field observation data with data form micro-plots in a few years. Besides, the micro-plot method is less expensive and simpler to conduct.

However this model used field observation data only in a sub-catchment. More experiments are needed to test the FUSLE model in catchments scale and this will be reported in future work.

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