The CSLE model based soil erosion prediction: Comparisons of sampling density and extrapolation method at the county level

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ABSTRACT

The Universal Soil Loss Equation (USLE) is an empirical equation commonly applied to predict soil erosion throughout the world. In China, the Chinese Soil Loss Equation (CSLE) has been developed for estimating annual soil erosion by water on the basis of the USLE. It is proven that two factors (i.e., sampling density and extrapolation method) are important in the application of CSLE for soil erosion survey and evaluation. In this study, based on the SPOT 6 image (1.5 m resolution) and the 1:10,000 topographic map in Yishui county of the Yimeng Mountain Area (YMA), eastern China, two sampling densities (1% and 4%) were selected and three extrapolation methods (grid based calculation, direct extrapolation, and Kriging extrapolation based on sampling units) were adopted to compare their effect on the CSLE calculated soil erosion condition and status. Results showed that estimated soil erosion by direct extrapolation and Kriging extrapolation methods varies largely with sampling density. The discrepancy of the soil erosion area ratios calculated by the two methods are 6.5% and 7.7% under the 1% and 4% sampling density, and the relative discrepancies are 15.9% and 16.2%, respectively. But the grid calculation method is less affected by sampling density. The discrepancy of soil erosion area ratios is only 0.9% and 2.0%, respectively, under the 1% with 4% sampling density. Considering both field workload and prediction accuracy of soil erosion, the 1% sampling density with the grid calculation method is recommended when high resolution remotely sensed data are available. Otherwise, the 4% sampling density with either extrapolation method should be used. The research can provide useful reference information for ensuring the accuracy and reducing the survey workload on the application of CSLE in other areas.

1. Introduction

Soil erosion prediction and assessment has been a challenging research topic due to nonstationary and heterogeneous characteristics of the geomorphic process of soil erosion on the Earth's surface (Olexandr et al., 2009). Basically, soil erosion status and hazard can be assessed and predicted by expert scoring and analysis, sampling-based methods, and model-based methods based on soil, vegetation, and land use data (Zhang et al., 2013; Aiello et al., 2015; Huang et al., 2016). With the advancement of spatial technologies and soil sampling tools in developed regions, the method of soil erosion surveying has evolved from qualitative assessment to comprehensive, systematic quantitative analysis and prediction (Anton, 2006). And quantitative assessment integrates sampling data and soil erosion models for large scale evaluation and prediction of soil erosion status and hazard. For example, in the United States, integrating soil survey data and soil erosion models, including USLE (Universal Soil Loss Equation; Wischmeier and Smith, 1978), RUSLE (Revised Universal Soil Loss Equation; Renard et al., 1997), and WEQ (Wind Erosion Equation; Woodruff and Siddoway, 1965) have been applied to evaluate and predict soil erosion hazard (Smith, 1941; Nusser and Geobel, 1997; Jeffery, 1998; United State Department of Agriculture, 2009). In Europe, the expert scoring method and models, including USLE, EUROSEM (European Soil Erosion Model) (Morgan et al., 1998), and LISEM (Limburg Soil Erosion Model) (De
Roo, 1996) are widely adopted to evaluate soil erosion (Lu et al., 2001; Grimm et al., 2002).

China is one of the most populated countries in the world and soil erosion by water, which is mainly triggered by high-intensity human activities such as deforestation, urbanization and land use change, has become a national environmental issue (Zhang et al., 2008). Great efforts in soil erosion control measures and soil erosion status and hazard evaluation and prediction have been undertaken since the middle of the twentieth century. Three nationwide soil erosion surveys have been completed based on land use, slope, and vegetation coverage data derived from the remote sensing technology since the 1980s (Ministry of Water Resources of PR China, 2002; Guo and Li, 2009). The national soil erosion survey provides baseline information on soil erosion status and hazard at the national scale. However, such surveys are greatly limited for regional or small-scale soil erosion control and conservation planning due to 1) relatively coarse resolution of TM image, 2) exclusion of driving factors of soil erosion at local scales, and 3) qualitative or semi-quantitative nature in soil erosion evaluation and prediction. To better predict soil erosion processes at fine scales, the Chinese soil loss equation (CSLE), an improved version of USLE, was developed for quantitatively evaluating soil erosion considering the characteristics of landform and soil and water conservation measures in China (Liu et al., 2002). CSLE coupled with field survey, a stratified random sampling data with unequal probabilities, was first utilized to evaluate national soil erosion conditions from 2010 to 2012 (Leading group office of first-ever nationwide water resources census of the State Council of China, 2010). The sampling density of survey units was 1% in most areas, but only 0.25% for plain areas and less disturbed mountain areas (Liu et al., 2013; Li et al., 2012; Liu, 2013).

Previous studies suggest that sampling density and extrapolation method are two important factors in model-assisted soil erosion evaluation and prediction (Zhang et al., 2012, 2013). Studies have shown that different sampling densities could result in discrepancies in the calculation results of CSLE. Zhang et al. (2012) used the CSLE model to estimate soil erosion based on a 1% sampling density in Wuqi county of Shaanxi Province, China and found that the method was more effective than other commonly used methods before. Zhao et al. (2012, 2013) further compared and analyzed the accuracy loss in land use, slope and slope length of four sampling densities, including 4%, 1%, 0.25%, 0.0625%, and found that 1% sampling density could better estimate soil erosion conditions at a reasonably low error rate. However, it remains unknown how different extrapolation methods may interact with sampling density and affect estimation results. Zou et al. (2016) took Mengyin county located in Yimeng mountain area as example to analyze the influence of different sampling densities and extrapolation methods on the soil erosion amount at the county scale, and to determine the appropriate sampling density and extrapolation in the premise of guaranteeing the suitable precision and workload in the soil erosion survey.

The primary objective of this study was to compare how two sampling densities interact with three commonly used extrapolation methods to affect the estimation results of CSLE and to select suitable sampling density and extrapolation method taking into account field workload and prediction accuracy of soil erosion. Specifically, we selected Yishui county, a typical county of National Key Harnessing Area of Yimeng Mountains as our study area to compare the difference and evaluate associated factors of CSLE assisted soil erosion conditions under the sampling densities of 1% and 4% and three extrapolation methods, including direct extrapolation, Kriging extrapolation and grid calculation. The results will provide useful information on the application of CSLE in other areas and determination of the efficient sampling density and extrapolation method to ensure the accuracy but also reduce the survey workload for evaluating soil erosion.

2. Materials and methods

2.1. Study area description

The study was conducted in Yishui county of Linyi city, located in the Yimeng Mountain Area (YMA), Shandong province, mid-eastern China (Fig. 1). The geographical coordinates are 35°55′2″ to 36°12′25″ N and 118°11′10″ to 119°3′34″ E, covering an area of 2420.1 km². It has a continental warm monsoon climate. The average annual temperature is 12.3 °C. The average annual precipitation is 629.2 mm. The topography of this area is characterized by low mountains and hills, accounting for 94.3% of the total area. The altitude above sea level is between 100 m and 900 m, and decreases from the northwest to the southeast. The soil types of this area are typically of skeleton soils (predominately sand and gravel) commonly found in mountainous areas, brown earth, cinnamon soil, red clay and moist soil according to the Chinese Soil Taxonomic Classification. The zone vegetation type of this area is warm temperate deciduous broad-leaf, which is mostly plantation vegetation. Common types of arboreal vegetation in the area include Platycladus orientalis, Zanthoxylum bungeanum, Robinia pseudoacacia, and Pinus densiﬂora. Herb and shrub vegetation mainly include Vitex negundo heterophylla, Lespedeza bicolor, and Spiraea trilobata.
2.2. Data sources and land use data interpretation

Data used for this study mainly include a high resolution (1.5 m) SPOT 6 imagery taken in April 2013, a 1:10,000 topographic map, a 1:500,000 soil classification map and the daily precipitation data from 88 weather stations in the study area between 1980 and 2010 for obtaining the needed factors estimating soil erosion. And the runoff plot data observed from four monitoring sites in Jiuxianshan, Linqu, Mengyin, and Huangqian, from 1980 to 1990 and from 2007 to 2012 are collected to validate the calculated soil erodibility data and the estimated soil erosion intensity. These collected monitoring data includes the soil erosion amount under different soil types based on the standard runoff plot with 20 m × 5 m and 5’ in China and the soil erosion amount under different soil and water conservation measures, which can be used to validate the calculated soil erodibility data under corresponding soil types and the estimated soil erosion intensity under corresponding land use types and soil and water conservation measures. All spatial data layers were georeferenced and transformed to the World Geodetic System 1984 (WGS1984) for spatial analysis and information extraction in ArcGIS.

Based on the characteristics of remote sensing image, combined with field investigations in September of 2013 and laboratory analyses, the interpretation signs for the SPOT 6 images were established and the detailed land use information was extracted using human-computer interaction interpretation method. The derived land use data have an accuracy of > 90% based on field survey data and will be used to estimate soil erosion status. Except for land use data, it can also be acquired part of the soil and water conservation measures like vegetation coverage and terraces from the SPOT 6 images.

2.3. Spatial sampling design, field survey and data collection

Based on pilot studies, two sampling intensities of 1% and 4% were chosen for field data collection to estimate soil erosion. To set up field investigation unit (FIU), the study area was first divided into a grid of 10 × 10 km² area (approximately equal to the average township area) using the Gauss-Kruger project method (Liu et al., 2013); each 10 × 10 km² area was further divided into four 5 × 5 km² subareas (approximately equal to the average watersheds size); and finally, the 5 × 5 km² subarea was divided into twenty-five 1 × 1 km² FIUs (Fig. 2). A stratified systematic random sampling scheme was used to deploy sample locations among the FIUs with 24 and 96 FIUs were selected, respectively, at the 1% and 4% sampling intensities (Leading group office of first-ever nationwide water resources census of the State Council of China, 2010; Liu et al., 2013; Li et al., 2010). Considering low soil erosion rates in plain areas, the actual sampling intensity was controlled subjectively to remain approximately 1% in these areas, but more sample locations were allocated in piedmonts or hilly areas under the 4% sampling intensity (Fig. 3). Field survey data were measured and collected in the 1 × 1 km² FIU in plain areas and in a 0.2–3 km² water catchment area (WCA) including the sampled 1 × 1 km² FIU and surrounding areas. Based on SPOT 6 images, superimposed terrain elements, FIU boundaries and other information, the field survey map were made to carry out the field investigation in September 2013. Through field investigation and instrument measurement, the field survey information was required including land use condition, forest canopy density, ground vegetation coverage, biological and engineering measures and quality, and cultivation measures (Leading group office of first-ever nationwide water resources census of the State Council of China, 2010; Li et al., 2010). The quality of field investigation in FIU was controlled by examining if the survey form information and photograph were complete, if the problematic areas were solved well and if it was right for the survey result and soil erosion intensity in order to make sure the estimated accuracy.

2.4. Parameterization of the CSLE model

The CSLE model (Liu et al., 2002) was proposed to reflect the characteristics of landform and soil and water conservation measures in China on the basis of USLE. The equation was expressed as follows:

\[ A = R \cdot K \cdot L \cdot S \cdot B \cdot E \cdot T \]  

(1)

where \( A \) is the annual average soil erosion amount (t/hm²⋅a); \( R \) is the factor of rainfall erosivity (MJ·mm/(hm²·h·a)); \( K \) is the factor of soil erodibility (t·hm²-h/(hm²·MJ·mm)); \( L \) is the dimensionless factor of slope length; \( S \) is the dimensionless factor of slope steepness; \( B \) is the dimensionless factor of biomass-control in water and soil conservation; \( E \) is the dimensionless factor of engineering-control in water and soil conservation; \( T \) is the dimensionless factor of tillage practices in water and soil conservation. The parameterization of the CSLE model was described as follows.

\( R \): To evaluate the \( R \) (rainfall erosivity) factor in the equation, the precipitation data from the 88 rainfall stations in YMA between 1980 and 2010 were used. The rainfall erosivity was calculated using daily precipitation data according to the method proposed by Yu and Rosewell (1996) and Zhang et al. (2002) and was extrapolated to the entire study area through the kriging method (Yang, 2014).

\( K \): Soil samples of each soil type were collected at three different times in August 2013 to measure the composition of particle size and organic matter. Soil erodibility was computed using the Williams model (United States Department of Agriculture, 1990) and proportionally modified according to the observation data of a runoff plot (Yang, 2014) to maintain the accuracy and quality of the estimated soil erodibility data (Olson and Wischmeier, 1963; Young and Mitcheler, 1977).

\( LS \): The slope length and slope steepness were calculated by the algorithm modified by Liu and others (Liu et al., 2002; Liu et al., 1994; Liu et al., 2000) based on the 1:10,000 topographic map and adjusted to the real condition of the field investigation units (Yang, 2014).

\( BET \): The factors of water and soil conservation were estimated depending on the different land use types based on the reference value provided by the first-ever nationwide water resources survey between 2010 and 2012 (Leading group office of first-ever nationwide water resources census of the State Council of China, 2010) and modified according to the data of field investigation units, runoff plots, and vegetation coverage (Yang, 2014).

The above factors were converted into raster layers with a resolution of 10 m. The soil erosion modulus (intensity) of the investigation units was calculated as a superposition of \( R \), \( K \), \( LS \), \( BET \) raster layers (Eq. (1)). Based upon the technical standards for comprehensive treatment of water and soil erosion in the earth rock mountain areas of northern China (SL 665–2014) (Ministry of Water Resources of PR China, 2014), the calculated soil erosion intensities were classified into six soil erosion (t/km²⋅a) classes: < 200 (slight), 200–1000 (low), 1000–2500 (moderate), 2500–4000 (high), 4000–6000 (extremely high) and > 6000 (severe). The soil erosion calculation results were compared with the soil erosion situation in the field investigation or the runoff plot observation data under corresponding land use type and soil and water conservation measures to validate the rationality of estimation results.

2.5. Extrapolation of soil erosion for the study area

Considering the spatial variation of soil erosion factors in model (1) and resultant soil erosion intensities, three extrapolation methods—direct extrapolation, Kriging extrapolation and raster extrapolation were
used to estimate soil erosion condition for the unsampled areas and the study area as a whole (Yishui county) based on sample data collected on the 24 (1% sampling intensity) and 96 (4% sampling intensity) FIUs and/or WCAs. Differentiations of these three extrapolation methods were described as follows.

Direct extrapolation simply assigns the calculated soil erosion intensity (Eq. (1)) for a FIU or WCA to its controlling area and then calculates the area of soil erosion in different erosion classes for the study area based on the following equations.

\[ N_j = \frac{D_j}{M_j} \times 100\% \]  

(2)
3. Results and discussion

3.1. Difference in estimated soil erosion area between two sampling densities with the same extrapolation method

With the direct extrapolation method, soil erosion in Yishui county was mainly dominated by the low and moderate erosion classes. The estimated total soil erosion area of Yishui county was 832.9 km² (34.4%) and 990.0 km² (40.9%) under the 1% and 4% sample density, respectively. The relative difference in estimated erosion area between these two sampling densities increases with erosion class, reaching up to 42.3% for the extremely high class and 96.0% for the severe class, with a significant overall relative difference of 15.9% at the 90% confidence level.

With the Kriging extrapolation method, soil erosion in Yishui county was dominated by the low and moderate erosion classes. The estimated total soil erosion area of Yishui county was 811.9 km² (35.6%) and 980.0 km² (41.2%) under the 1% and 4% sampling density, respectively, which are comparable to those of the direct extrapolation method. The relative difference in estimated erosion area between these two sampling densities increases with erosion class, reaching up to 130.0% for the severe class, with a significant overall relative difference of 18.7% at the 90% confidence level. Both sampling densities indicate that high erosion classes occurred in the western part (mountainous area) and some moderate erosion was found in the northeastern part, but the 4% sampling density reveal more local or focal variation of higher erosion classes (Fig. 4). According to the prediction errors (Table 1), the image result of 4% sampling density was better than that of 1% sampling density. Compared to the prediction errors of 1% sampling density, the RMS (Root-Mean-Square) and ASE (Average Standard Error) were closer, and the Root-Mean-Square Standardized was lower under 4% sampling density.

Export Result Table Compared to the direct and Kriging extrapolation method, the grid method showed a slightly higher total erosion area of 1053.1 km² (43.5%) and 1074.2 km² (44.4%) under the 1% and 4% sampling density, respectively. Soil erosion was still dominated by the low and moderation erosion classes as shown by the other two extrapolation methods. However, the overall relative difference between two sampling densities was minimal 21.1 km² (2%) and not significant at the 90% confidence level. As the direct and Kriging method, differences were mainly found in higher erosion classes between the 1% and 4% sampling density, largely due to small erosion areas in higher erosion classes. The erosion maps for the 1% and 4% sampling density under the grid extrapolation method are nearly identical, depicting detailed spatial variation (a resolution of 10 m) of different erosion classes in the study area (Fig. 5).

Further analysis found that the primary reason for significant differences in estimated erosion area between the 1% and 4% sampling density under the direct and Kriging method was the discrepancy in slope estimation. The calculated average value of slope steepness factor for the 4% sampling density was higher than that of 1% sampling density in the CSLE model. For example, the percentage of slope < 5° estimated based on FIU for the 1% and 4% sampling density was 68.1% and 52.5%, respectively, and higher than the county level mean (51.8%), which caused the estimated soil erosion area to be low under the 1% sampling density. Sampling density does not affect the estimation in the grid extrapolation method, for slope was extracted from each pixel (a resolution of 10 m) of the raster image (layer).

3.2. Difference in estimated soil erosion area between different extrapolation methods under the same sampling density

Under the 1% sampling density, there was no significant difference in estimated erosion area as a whole and by erosion class between the direct and Kriging methods. Both methods, however, generated a significantly lower total erosion area (220.1 km² and 241.1 km²) less than...
Further comparisons by erosion class indicated that both methods significantly overestimated erosion area in the slight erosion class, but underestimated erosion area in the low and moderate erosion classes than the grid method. There was no significant difference in the high, extremely high and severe erosion classes among the three methods (Fig. 6). Compared to the grid method, kriging method resulted in a smoother erosion map due to the nature of interpolation which can generate a continuous surface from the discrete point data in order to understand the spatial distribution pattern of space objects using spatial interpolation module in ArcGIS (Figs. 4(a) and 5(a)).

Under the 4% sampling density, no significant differences were observed between the direct and kriging methods. Except for the moderate erosion class, the difference in estimated erosion area between these two methods and the grid method became less significant. Total erosion area estimated by both methods, for instance, was only 84.1 km² (3.5%) and 76.1 km² (3.2%) less than that by the grid method (Fig. 7). The erosion map generated by the kriging method identified several large patches of higher erosion classes, while the grid method depicted numerous small patches (Figs. 4(b) and 5(b)).

Zhao et al. (2012, 2013) found the 1% sampling density in Wuqi county of Shaanxi Province, China, was applicable to measure soil erosion factors and both the 1% and 4% sampling densities obtained an accuracy > 95% at the county level. However, our results indicate that sampling density has a greater impact on results with the direct extrapolation and Kriging extrapolation based on FIUs and suggests the superiority of the 4% sampling density if the direct and kriging methods were used. The 1% sampling density was feasible in Yishui county with the grid extrapolation method when additional topographic data and high resolution satellite data were available. Wuqi county, located in the Loess hilly region, is dominated by loess soil, low population intensity and homogeneous underlying surface, while Yishui county, located in YMA, is mainly skeleton soil, and has a large population...
density and land use fragmentation. The discrepancy of estimated soil erosion factors was less between the 1% and 4% sampling densities in Wuqi county, but significantly large in Yishui county, and subsequently a large difference in soil erosion area estimated by the direct extrapolation or Kriging extrapolation method.

3.3. Difference in estimated soil erosion area by extrapolation method and sampling density

Soil erosion area estimated by the direct and kriging extrapolation methods increased significantly with sampling density compared to the slight increase of the grid method (Table 2). Taking the grid method as the base line, the relative differences of soil erosion areas calculated by the Kriging extrapolation method and direct extrapolation method were 22.9% and 20.9%, respectively, under 1% sampling density. Also, the average relative differences in different soil erosion intensity were 24.8% and 22.7%, respectively. The relative difference of soil erosion area dropped to 7.1% and 7.8%, respectively, under 4% sampling density. Also, the average relative differences of different soil erosion intensities dropped to 10.0% and 9.7%, respectively. Therefore, soil erosion area calculated by direct extrapolation method and Kriging extrapolation method was very close under the same sampling density, but the results of both methods were different from those of the grid calculation method, with large discrepancy in 1% sampling density, while only a small discrepancy under 4% sampling density.

Direct extrapolation and Kriging extrapolation methods are simple to operate but field data collection is needed and calculation results are easily influenced by sampling density. The direct extrapolation method cannot generate a sketch of soil erosion distribution and fail to present spatial information, while the Kriging extrapolation method can only generate a distributional map of soil erosion and provide a general trend of soil erosion. The grid calculation method makes high demands for basic data, especially for detailed land use data from high resolution satellite data. However, this method is less affected by sampling density, and the use of 1% sampling density not only reduces the field workload effectively but also obtains better results of soil erosion calculation.

4. Conclusions

The grid calculation method is less affected by different sampling densities than the direct extrapolation method and Kriging extrapolation method. The results of soil erosion calculated by the direct extrapolation method and the Kriging extrapolation method are similar, but quite different from the results of the grid calculation method, under the same sampling density. Relatively speaking, the results calculated by the direct extrapolation and Kriging extrapolation under the 4% sampling density are closer to those of the grid calculation than 1% sampling density.

The estimated soil erosion area under 1% sampling density by the extrapolation method tends to be smaller than that under 4% sampling density, mainly because of the effect of slope calculation.

As a result, the extrapolation method should be used with 4% sampling density to calculate soil erosion by CSLE at county-level. The
grid calculation can be used with 1% sampling density, when high-resolution land use and topological data are necessary, which needs less field workload and improves the accuracy of the soil erosion calculation results.

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References


Table 2

<table>
<thead>
<tr>
<th>Estimation method</th>
<th>Direct extrapolation</th>
<th>Kriging extrapolation</th>
<th>Grid calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area/km²</td>
<td>Percent/%</td>
<td>Area/km²</td>
</tr>
<tr>
<td>1% sample density</td>
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<td>34.42</td>
<td>811.94</td>
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<tr>
<td>4% sample density</td>
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<td>Discrepancy</td>
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<td>~19.29</td>
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<tr>
<td>Average difference</td>
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<td>~18.65</td>
<td>~19.29</td>
</tr>
</tbody>
</table>

Note: Discrepancy of area/percent = The result of 4% - The result of 1% The relative difference = [The result of 1% - The result of 4%] / The result of 4% × 100%. Average difference = E (Relative difference of different soil erosion intensity * Corresponding percent of soil erosion intensity).

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