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Quantitative Assessment of Soil Erosion Based on CSLE and the 2010 National Soil Erosion Survey at Regional Scale in Yunnan Province of China

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Abstract: Regional soil loss assessment is the critical method of incorporating soil erosion into decision-making associated with land resources management and soil conservation planning. However, data availability has limited its application for mountainous areas. To obtain a clear understanding of soil erosion in Yunnan, a pixel-based estimation was employed to quantify soil erosion rate and the benefits of soil conservation measures based on Chinese Soil Loss Equation (CSLE) and data collected in the national soil erosion survey. Results showed that 38.77% of the land was being eroded at an erosion rate higher than the soil loss tolerance, the average soil erosion rate was found to be 12.46 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$, resulting in a total soil loss of 0.47 Gt annually. Higher erosion rates mostly occurred in the downstream areas of the major rivers as compared to upstream areas, especially for the southwest agricultural regions. Rain-fed cropland suffered the most severe soil erosion, with a mean erosion rate of 47.69 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$ and an erosion ratio of 64.24%. Lands with a permanent cover (forest, shrub, and grassland) were mostly characterized by erosion rates an order of magnitude lower than those from rain-fed cropland, except for erosion from sparse woods, which was noticeable and should not be underestimated. Soil loss from arable land, woodland and grassland accounted for 52.24%, 35.65% and 11.71% of the total soil loss, respectively. We also found significant regional differences in erosion rates and a close relationship between erosion and soil conservation measures adopted. The CSLE estimates did not compare well with qualitative estimates from the National Soil Erosion Database of China (NSED-C) and only 47.77% of the territory fell within the same erosion intensity for the two approaches. However, the CSLE estimates were consistent with the results from a national survey and local assessments under experimental plots. By advocating of soil conservation measures and converting slope cropland into grass/forest and terraced field, policy interventions during 2006–2010 have reduced soil erosion on rain-fed cropland by 20% in soil erosion rate and 32% in total soil loss compared to the local assessments. The quantitative CSLE method provides a reliable estimation, due to the consideration of erosion control measures and is potentially transferable to other mountainous areas as a robust approach for rapid assessment of sheet and rill erosion.

Keywords: spatial quantification; regional soil loss assessment; sampling survey; CSLE; soil conservation measures

1. Introduction

Soil erosion is regarded as one of the most serious and widespread forms of soil degradation, and as such, poses a severe threat to the sustainability and productive capacity of agriculture and terrestrial ecosystems [1–3]. During the last 40 years, nearly one-third of the world's cultivated land has been lost, due to soil erosion, with loss continuing at a rate of more than 10 million hectares per year [4]. Apart from causing on-site impacts, such as reduced soil fertility and productivity, thinner plow layer and poor water holding capacity, the transport of sediments can easily degrade streams, lakes and estuaries, which leads to increased flood risk, reduced lifetime of reservoirs and destruction of habitats [5–7]. Considering the slow soil formation rates, the soil has become a nonrenewable resource to some extent and difficult to reclaim when eroded [8]. In the last few decades, the importance of protecting and restoring the soil resources from erosion has been increasingly recognized by scientists and policymakers around the world.

In order to monitor and assess the environmental and social impacts of soil erosion and to make management strategies to deal with them, quantitative information on soil erosion rates at a regional scale is needed [6,9]. Additionally, formulation of suitable remediation measures, allocation of scarce soil conservation resources and development of policies and regulations also require a clear understanding of the distribution characteristics of erosion at a regional scale to avoid waste [10,11]. Therefore, quantitative soil erosion assessment at a regional scale for sustainable agriculture and environment is essential.

Although a wide variety of approaches have been employed to assess soil erosion caused by water in different regions around the world. For a long time, quantitative studies have been focused on the scales of plot size, hill-slope and catchment. Methods applied at small scales, such as direct observation, erosion tracer methods, sediment concentration measurement mostly become impractical, due to the large temporal and spatial variability of soil erosion affecting factors [12]. The demand for credible information on regional-scale erosion and the environment has led to the development of many monitoring efforts, inventory programs, and inter-agency cooperation for erosion assessment data collection. Along with these efforts devoted, methods of regional scale soil erosion assessment also developed [13–15].

At present, the general approaches to regional soil loss assessment can be divided into several categories [14]. The first category includes an assessment based on a sample survey and distributed point/area data. The well-known example of sample survey is the National Resource Inventory (NRI) conducted by the US Department of Agriculture’s Natural Resources Conservation Service (NRCS) for decades [16], which employs Universal Soil Loss Equation (USLE) and its revised version RUSLE [17,18] to estimate long-term averages of sheet and rill erosion. Others focused on the extrapolation of data from experimental runoff plot and field-based measurements to regional scale. For example, Cerdan et al. (2010) extrapolated measured data from erosion plots under natural rainfall and revealed that the mean rill and inter-rill erosion rates are 1.2 t ha^{-1} yr^{-1} for the whole CORINE area and 3.6 t ha^{-1} yr^{-1} for arable land in Europe [19]. Based on runoff plot data, Guo et al. (2015) analyzed the soil loss rate range for the five water erosion regions in China and reported values of 30.87–107.44 t·ha^{-1}·yr^{-1} on fallow land and 7.65–49.38 t·ha^{-1}·yr^{-1} on farmland [20]. Evans et al. (2016) extrapolated field-based data across the landscape and clarified the extent and frequency of water erosion rate from arable land in Britain [21]. Xie et al. (2019) quantified soil erosion changes in cropland in northeastern China over the past 300 years using data form field survey and historical cropland areas [22]. However, it is important to note that the direct extrapolation may cause poor estimation of regional soil erosion rates if the scale issue is not carefully considered [19]. The second category includes qualitative methods of factorial approaches and expert-based methods. A representative example is the national soil erosion remote sensing investigations conducted in China. By using the Landsat TM data and 1:50,000 relief map, a man-computer interactive interpretation was employed to determine soil erosion intensity based on performance in slope and vegetation cover [23]. Other studies include soil erosion risk assessment using the GLASOD method [24] and the CORINE approach [25]. The third category includes model-based grid estimation of empirical, physical and distributed models. The typical example is soil erosion risk assessment in Europe based on various methods, such as the PESERA method [26], the EUROSEM method [27] and the recent assessments using the EIONET network [28]. By using a modified version of RUSLE, Panagos et al. (2015) reported that the mean soil loss rate and total soil loss from European Union's erosion-prone lands were 2.46 t ha^{-1} yr^{-1} and 970 Mt [29]. Karamage et al. (2016) assessed the soil erosion rate of Rwanda using RUSLE and Landsat OLI data and found that cropland erosion was responsible for approximately 95% of the country's soil loss [30]. De Vente et al. (2008) quantified soil erosion and sediment yield at regional scales in Spain using three distributed models of WATEM-SEDEM model, the PESERA model and SPADS [13]. However, for application at the regional scale, most erosion models are severely limited by their high data demand [15]. Each of these categories has its own advantages and disadvantages, sampling survey and runoff plot data provide the most detailed information on erosion, but requires a lot of field work, model based-grid estimation and qualitative methods usually provide a full-coverage evaluation, but rarely take the soil conservation measures into consideration, due to the spatial resolution limitations, thereby the results are usually expressed as soil erosion risk, which cannot provide precise soil loss rates and reflect the benefits of soil conservation measures. In general, the availability and quality of input data is probably the most important consideration when selecting an assessing method at a regional scale [25].

In 2010 through 2012, by using unequal probability sampling methods and the Chinese Soil Loss Equation (CSLE) model, the Ministry of Water Resources of China (MWRC) conducted the fourth national soil erosion survey [14,23,31], known as the 2010 NSES. Different from the previous three qualitative soil erosion surveys using satellite imagery, this is the first ever national survey to incorporate sampling survey, field investigation, model-based calculation and latest spatial information techniques in China's history to quantify soil erosion. Sampling investigation is the main method of the survey. According to the erosion types involved and actual situations of each province in China, a total of 33,966 primary sample units (PSUs) were determined and allocated in the field with sampling densities of 4%, 1%, 0.25% and 0.0625%. Each PSU is a 1 km × 1km grid in the plain area or a small watershed with area from 0.2 to 3.0 km^2 in the mountainous area, which was selected for investigation [32]. Thousands of data gathered in the country were instructed to visit every land parcel (defined as land with same land use and conservation practice) in each PSU and collect indicators of soil erosion in the field. The data collected concerning the erosion affecting factors share uniform standards and specifications and was well-examined in every step of the survey. After a comprehensive analysis of rainfall, soil, terrain, land use and soil conservation practice, the soil erosion rate was computed by CSLE model with a spatial resolution of 10 m for each land parcel, then statistical methods were applied to evaluate the distribution, area and intensity of soil erosion at PSU, county, provincial and national levels [22]. Yunnan, as one of the mountainous provinces suffering from severe soil erosion, received a lot of attention in the national survey for its complex erosion conditions and irreplaceable ecological value. Little published work is available of soil erosion rates or soil conservation measures in Yunnan so far, due to the steep topographic conditions, complex crop rotation system and various soil conservation measures.

The objectives of this paper are: (a) To quantify soil erosion by water in Yunnan using CSLE and available PSUs data in the 2010 NSES; (b) to study soil erosion variations and regional differences under different land use types in Yunnan; (c) to compare the CSLE method with the traditional qualitative RS approach, the comparison aims to clarify the advantages and disadvantages of the methods and thereby contribute to the rational selection of the suitable methods for regional soil erosion assessment; (d) and to analyze the effectiveness of policy interventions on soil erosion reduction by comparing the results to previous local studies.

2. Materials and Methods

2.1. Study Area

Yunnan Province is situated in the extreme southwest of China, and lies between 21°09′–29°15′ N and 97°32′–106°12′ E (Figure 1). The province covers an area of more than 3.83×10^5 km^2, bordering the Himalayas and Myanmar in the west, Vietnam and Laos in the south. Altitude in Yunnan varies considerably, from less than 100 m of the Red River at the southeast edge to more than 6700 m in the northwest mountainous areas, with an average value of approximately 2000 m. High mountains and deep valleys characterize the western parts, whereas in eastern Yunnan, rivers generally flow in relatively shallow valleys, forming a landscape tilting from the northwest to the southeast. Affected by monsoons and the west-wind circulation, the climate is typical sub-tropical monsoonal, though relatively mild, due to the high altitude [33]. Precipitation is abundant, but unevenly distributed in time and space, ranging from less than 600 mm in dry valleys to more than 2000 mm in the southern mountainous areas, with a mean value of 1100 mm. About 85% of the annual precipitation is concentrated in the months from May to October [34]. The major soil groups (FAO/UNESCO classifications) in the province are: Acrisols (34.44%) that mainly distributed in southern Yunnan, Cambisols (25.12%) that mainly distributed in the central portion, Luvisols (22.44%) that mostly distributed in the northwest, Alisols (7.36%) that mainly distributed in the tips of southwest, southeast and northeast, and Anthrosols (4.39%) that dispersed in the whole province (Figure 2b). Both Acrisols and Alisols are rich in clay and formed under great precipitation and high temperature conditions, while Luvisols is characterized as a kind of soil that clay has been leached after snowmelt or heavy rains. Cambisols are generally developed in medium and fine-textured materials. Rice, wheat and maize are the principle food crops grown, while tea, sugar cane, tobacco and rubber are the main cash crops. The topographical variety also contributes to a vast territory with diversified and unique natural resources. Spinning only 8° in latitude, the province holds all the land ecosystems that can be found in the 35° range of latitudes of the country [35]. Six major rivers flow through the province, among which the Irrawaddy, the Salween, the Mekong and the Yangtze originate from the Qinghai–Tibet plateau. Two other rivers, the Red and the Pearl originate from the province itself. The population of Yunnan in 2010 was 46 million (National Bureau of Statistics of China, 2010). With some 84% of the province classed as mountains and the plain areas already fully utilized for agriculture, pressure on remaining land resources is high.

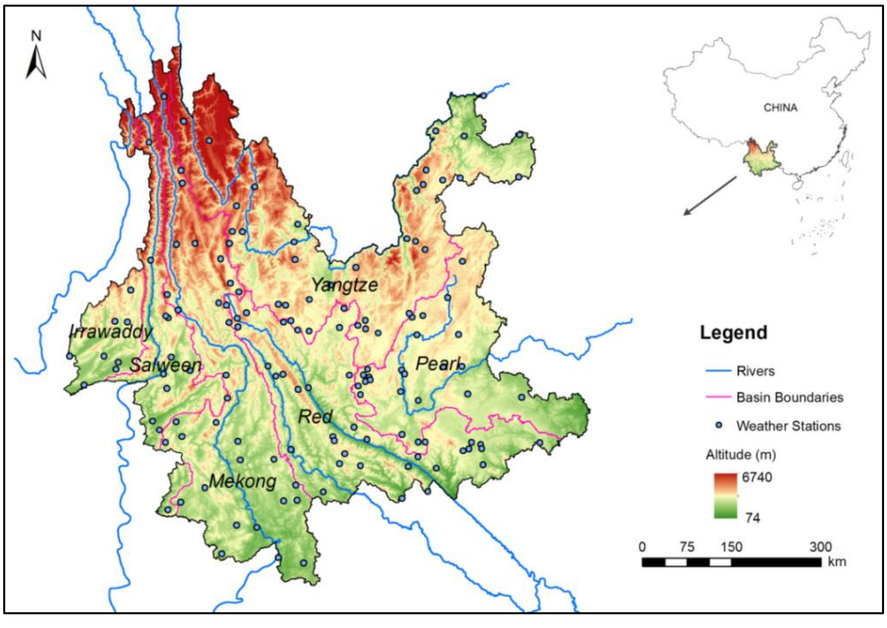

Figure 1. Map of Yunnan showing major rivers, basins, weather stations and altitude variation.

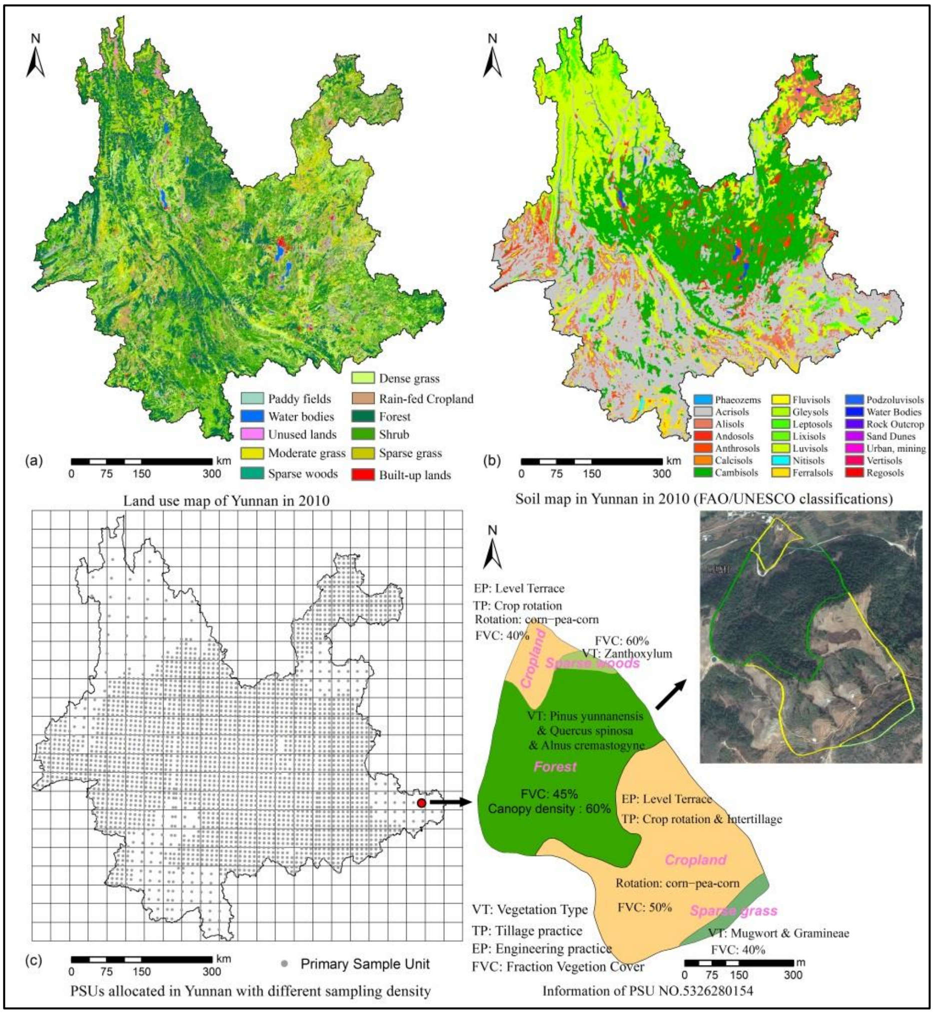

Figure 2. Maps of Yunnan showing: (**a**) Land use types; (**b**) Soil groups; (**c**) Primary sample units (PSUs) allocated in the National Soil Erosion Survey; (**d**) an detailed PSU example.

2.2. Data Sources

The major factors that determine the magnitude of soil erosion rate are rainfall, the nature of the soil, vegetation cover, the tillage practices used and mechanical farming measures, such as terracing and contouring [7]. Critical data concerning these factors in the study were obtained as follows:

Daily erosive rainfall (≥12mm) data from 143 meteorological stations in Yunnan for three decades (1981–2010), provided by the National Meteorological Data Sharing Service System (http://data.cma.cn), was used to develop an average annual rainfall erosivity map. Soil maps retrieved from the Second National Soil Survey (http://westdc.westgis.ac.cn) were used to develop a soil erodibility map. ASTER GDEM datasets (http://www.usgs.gov) at a spatial resolution of 30 m were prepared to derive topographical parameters. The remote sensing data used to calculate the vegetation cover consists of three aspects. The 250 m MODIS NDVI data, the 30 m HJ multi-spectral reflectance data (http://www.cresda.com) and a land use map. The land use datasets of Yunnan in 2010 (Figure 2a) was retrieved from the National Land Use/Cover Database of China (NLUD-C) at the scale of 1:100,000, developed by CAS. NLUD-C was derived from the Landsat TM/ETM data at a spatial resolution of 30 m and used for the land use/cover related assessment as it is the most well-known land use classification in China. The database includes seven datasets of land use status of China in the 1980s, 1995, 2000, 2005, 2008, 2010 and 2015, along with six corresponding datasets describes land use change information during these periods. Land use types are classified into six first-level types (arable land, woodland, grassland, water bodies, built-up land and unused land) and 25 corresponding second-level types [36]. Woodland is the most dominant land use type in 2010, which accounts for 57.64% of the province, grassland accounts for 22.55%, arable land covers 17.80% of the area, unused land, built-up land and water bodies take up 2.01%. Figure 2c shows the 2871 primary sample units (PSUs) allocated in Yunnan from the 2010 National Soil Erosion Survey, which were provided by Beijing Normal University (Technical support unit of the national survey) and integrated into land use datasets to generate raster layers of soil conservation measures. Figure 2d shows a specific PSU in the field and information for each land parcel within the PSU.

All these data were converted to a 30 m spatial resolution before incorporated as input layers in the CSLE model for further analysis.

2.3. *Quantitative Pixel-Based Estimation Using CSLE Model and PSUs Data*

By adapting parameters of USLE to the target areas, many Chinese scholars have proposed some regional soil loss prediction models for soil loss estimation and soil conservation planning since the 1980s. In 2002, Liu et al. [37] developed the Chinese Soil Loss Equation (CSLE) model based on measured data from Chinese unit plot and numerous plots modified to Chinese unit plot. CSLE is a statistical relationship model that correlates soil loss rates and the affecting factors, which can be modified according to the local conditions and has been widely verified and applied in China. The CSLE formula is defined as follows:

$$A = R \times K \times L \times S \times B \times E \times T, \tag{1}$$

where A is the average annual soil loss, t·ha^{-1}·yr^{-1}; R is the average annual rainfall erosivity, MJ·mm·ha^{-1}·h^{-1}·yr^{-1}; K is the soil erodibility, t·ha·h·ha^{-1}·MJ^{-1}·mm^{-1}; L is the slope length factor and S is the slope steepness factor; B, E, T are the erosion-control practices of biological, engineering and tillage, respectively. The factors of topography and soil conservation measures are dimensionless.

2.3.1. Rainfall Erosivity (*R-Factor*)

The erosive force of rainfall and consequent runoff is referred to as rainfall erosivity or the *R-factor.* It reflects the potential ability of rainfall to cause erosion and has been widely used for empirical soil loss estimation for the past several decades. Its calculation, however, requires high temporal resolution hyetograph data that is rarely available at standard meteorological stations in many parts of the world [38,39]. Due to the limited availability, alternative approaches based on more commonly available data, such as daily, monthly, and annual rainfall data have been used. In this study, daily erosive rainfall data of three decades from 133 meteorological stations in Yunnan were used to estimate the *R-factor* using the Cold-Warm Season Daily Rainfall Model [40] in the national survey. The formula is expressed as:

$$R = \sum\nolimits_{k=1}^{24} R_k, \tag{2}$$

$$R_k = \frac{1}{N}\sum\nolimits_{i=1}^{N}\sum\nolimits_{j=0}^{m}\left(\alpha \cdot P_{i,j,k}^{1.7265}\right), \tag{3}$$

$$WR_k = \frac{R_k}{R}, \tag{4}$$

where R is the average annual rainfall erosivity (MJ·mm·ha^{-1}·h^{-1}·a^{-1}), k represents the 24 half months in a year, R_k is the average rainfall erosivity in the k-th half month (MJ·mm·ha^{-1}·h^{-1}·a^{-1}), N refers to the time series from 1981 to 2010, the term α is a value of 0.3937 for warm season (May to September) and 0.3101 for cold season (October to April), $P_{i,j,k}$ is the actual erosive rainfall (≥12 mm) of the j-th day in the k-th half month in the i-th year, m is the number of days with erosive rainfall in the corresponding half month. WR_k is the ratio of average rainfall erosivity in the k-th half month to the average annual rainfall erosivity, which reflects the seasonal distribution of rainfall erosivity. For each station, the *R-factor* was estimated for the period during 1981–2010 and Kriging was applied as the method of spatial interpolation to create an erosivity map.

2.3.2. Soil Erodibility (*K-Factor*)

Soil erodibility represents soil's susceptibility to being detached and transported by the actions of raindrops and runoff [41]. In USLE, it was defined as the average soil loss rate per unit of rainfall erosivity index from a cultivated continuous fallow plot, with a 22.1 m long 9% slope [42]. The *K-factor* was determined using the USLE equations [43] based on national soil survey data, and then adjusted using measured unit plot data and cropland plot data. The equations are:

$$K = \left[2.1 \times 10^{-4} M^{1.14}(12\text{–}OM) + 3.25(S\text{–}2) + 2.5(P\text{–}3)\right]/100, \quad (5)$$

$$M = N_1(100\text{–}N_2), \quad (6)$$

$$M = N_1(N_3 + N_4), \quad (7)$$

where K is soil erodibility, N_1 (particle size 0.002–0.1mm) is the percent of silt (0.002–0.05mm) plus very fine sand (0.05–0.1mm), N_2 (<0.002mm) is the clay fraction, (100–N_2) (0.002–2mm) represents all soil fractions other than clay, OM is the soil organic matter content (%), S is the soil structure code, and P is the soil permeability code.

2.3.3. Topographic Factors (*LS-Factors*)

Topographic factors include slope steepness factor and slope length factor. In the present study, a DEM-based procedure developed by Fu et al. [44] was employed to generate CSLE-based raster layers of *LS-factors*. The algorithms used in the procedure integrated the raster grid accumulation with maximum downhill slope methods similar to that proposed by Hickey [45]. The DEM datasets were derived from ASTER GDEM. The segment slope length equation proposed by Foster [46] was employed to calculate the *L-factor*, and *S*-factor follows the USLE equation for gentle slopes while a modification is made for steep slope conditions based on measured data [47].

$$S = \begin{cases} 10.8 \sin\theta + 0.03 & \theta \leq 5^\circ \\ 16 \sin\theta\text{–}0.50 & 5^\circ < \theta \leq 10^\circ \\ 21.9\ \sin\theta\text{–}0.96 & \theta > 10^\circ \end{cases}, \quad (8)$$

$$L_i = \frac{\left(\lambda_{out}^{m+1} - \lambda_{in}^{m-1}\right)}{\left[(\lambda_{out} - \lambda_{in}) \times 22.13^m\right]} \quad \begin{cases} m = 0.2 & \theta \leq 1^\circ \\ m = 0.3 & 1^\circ < \theta \leq 3^\circ \\ m = 0.4 & 3^\circ < \theta \leq 5^\circ \\ m = 0.5 & \theta > 5^\circ \end{cases}, \quad (9)$$

where Li is the slope length factor of the *i*-th pixel, λ_{out}, λ_{in} are the pixel exit and entrance slope lengths, and m is the slope length exponent depending on the slope.

2.3.4. Soil Conservation Practices (*BET-Factors*)

During the development of the historical agriculture traditions in China, the systematical measures for soil conservation formed. The major difference between CSLE and USLE is that soil conservation practice factors of crop management (*C-factor*) and erosion-control (*P-factor*) used in the USLE are described by three erosion-control factors of biological (*B-factor*), engineering (*E-factor*) and tillage (*T-factor*) according to Chinese soil and water conservation classifications [48]. In the 2010 NSES, investigation of these erosion control measures in PSUs was the major task and all the relevant attributes of these measures were obtained and recorded in the field.

Biological Practice *(B-Factor)*

The role of vegetation cover on preventing soil erosion is well recognized. To account for vegetation, a biological control practices factor *(B-factor)* has been used in erosion assessments in the CSLE. The *B-factor* only refer to the forest or grass plantation for reducing runoff and soil loss, vegetation cover for arable lands are not included. Similar to *C-factor* in USLE, B values are weighted average soil loss ratios (B_i), each of which represents the ratio of soil loss under current conditions of a certain period of time to the soil loss under unit plot conditions during the same period [49]. B_i changes as vegetation cover changes during the process of plant growth. The B value then represents the average of B_i values, each weighted by the portion of rainfall erosivity during the same time period.

In this study, the *B-factor* layer was acquired as follows: First, vegetation coverage fraction (*FVC*) of 24 half months across the year for different vegetation types were calculated based on NDVI derived from time series of remote sensing images and field survey. Land use classification was then used to obtain B values. For arable land, built-up land, water areas and unused land, B values were assigned directly based reported value in literature. For woodland and grassland, B value for each half-month period was calculated across the year, and the ratio of the corresponding half-month R_i value to annual R was used as the weight to calculate the annual average *B-factor* value. The *FVC* and *B-factor* are calculated using NDVI as follows:

$$FVC = \frac{(NDVI - NDVI_{soil})}{\left(NDVI_{veg} - NDVI_{soil}\right)}, \tag{10}$$

$$B = \frac{\sum_{i=1}^{24} B_i R_i}{\sum_{i=1}^{24} R_i}, \tag{11}$$

where FVC is vegetation coverage fraction; $NDVI_{\max}$ refers to the regional maximum NDVI; $NDVI_{\text{veg}}$ is the NDVI value of the pure vegetation pixels; $NDVI_{soil}$ is NDVI value of the pure bare soil pixels; R_i is the rainfall erosivity portion for the i-th half month; B_i is the *B-factor* of the i-th half month. The relationship between vegetation coverage fraction (*FVC*) and B value was compiled in Table 1, which was summarized in the 2010 NSES according to the literature [50].

Table 1. B values for grassland, shrub and woodland of different vegetation coverage fractions.

FVC (%)	Grassland	Shrub	Woodland Canopy Density (%)									
			10	20	30	40	50	60	70	80	90	100
0	0.516	0.614	0.438	0.426	0.414	0.402	0.390	0.378	0.366	0.354	0.342	0.330
10	0.345	0.310	0.317	0.309	0.301	0.293	0.285	0.276	0.268	0.260	0.252	0.244
20	0.242	0.200	0.196	0.192	0.187	0.183	0.179	0.175	0.171	0.166	0.162	0.158
30	0.017	0.150	0.149	0.146	0.143	0.140	0.137	0.134	0.131	0.128	0.125	0.122
40	0.110	0.105	0.102	0.100	0.098	0.096	0.095	0.093	0.091	0.089	0.087	0.085
50	0.073	0.065	0.072	0.071	0.070	0.068	0.067	0.066	0.065	0.064	0.063	0.062
60	0.042	0.040	0.042	0.041	0.041	0.040	0.040	0.040	0.039	0.039	0.038	0.038
70	0.028	0.027	0.027	0.027	0.027	0.027	0.026	0.026	0.026	0.026	0.025	0.025
80	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.012	0.012	0.012	0.012
90	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
100	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003

Engineering and Tillage Practices *(ET-Factors)*

In USLE, *P-factor* was defined as the ratio of soil loss with the practice applied to up-and-downslope cultivation. In CSLE, it is described as the engineering control measures (E) and tillage control measures (T) factors. Engineering measures refer to the changes of topography to reduce runoff and soil loss by engineering construction. Tillage measures refer to the measures taken by farmland equipment, such as the ways to improve soil resistance to erosion, and reduce erosion by increasing surface cover or increasing soil infiltration to achieve conservation purpose. The difference between them is that the latter does not change the topography and are only applied on the cropland [37]. Both *E-factor* and *T-factor* has a dimensionless range of 0–1. The smaller the value is, the better the soil conservation benefit of a certain measure is.

Of the six input factors in USLE, values of the *P-factor* are considered as the most uncertain and rarely taken into account in conventional soil erosion models as it is difficult to estimate [51]. Most studies estimate the *P-factor* values according to land use types or slope. In the 2010 NSES, through a large amount of literature and investigation, the preliminary crop rotation factors of ten crops in China were established [49]. *T-factor* values of 376 rotation systems were obtained and *E-factor* values of 112 categories were compiled [32,50]. For Yunnan Province, a total of 20,156 land parcels in the 2871 PSUs were visited. Attributes (type, area, area percentage, quantity, crop rotation system, vegetative coverage) of erosion control measures in all these land parcels were identified, measured and recorded and then assigned from reported values in literature and measured natural runoff plots data.

In this study, we integrated all these PSUs data with land use map to generate raster layers of soil conservation measures. Take *T-factor* of farmland as an example, first we figured out all types of tillage measures adopted in farmland parcels in a PSU, then an area weighted average method was employed based on reported values of these measures and their attributes (types, corresponding T values and area percentage) to calculate the mean *T* value for farmland in this PSU, finally, mean *T* values of all farmland PSUs were interpolated using the nearest neighbor interpolation method to generate the *T-factor* raster layer of farmland in the province. According to the field survey, the *E-T* measures that most commonly occurred in Yunnan and their corresponding *E-T* values were compiled in Table 2. Erosion control measures, such as terracing, contour cropping and film mulching accounted for a large proportion and generated huge impacts on soil erosion reduction.

Table 2. Major *E-T* measures adopted in Yunnan in the 2010 NSES and their corresponding values.

Engineering Measures	*E*-Value	Tillage Measures	*T*-Value
Sloping terrace	0.4	No-tillage	0.14
Level terrace	0.1	Lea farming	0.23
Fruit tree pit	0.1	Contour cropping	0.43
Slope protection	0.2	Contour cropping and crop rotation	0.17
Gully head protection	1.0	Inter-tillage	0.50
Intercepting drain	0.8	Cross slope intercropping	0.20
Diversion canal	1.0	Ridged-furrow	0.15
Urban settlement	0.1	Crop rotation	0.37–0.41
Rural settlement	0.2	Rotation and fallow	0.09
Level trench	0.3	Crop rotation and film mulching	0.20
Plain paddy	0	Intercropping and inter-planting	1.00
Check dam	0.6	Lea farming and fallow	0.05
Slope-separated terrace	0.2	Contour furrow planting	0.18
–	–	Inclined ridging	0.70

2.4. *Qualitative Assessment of Soil Erosion Intensity*

To compare the results estimated by the above method with estimates from the National Soil Erosion Database of China (NSED-C) based on the national soil erosion remote sensing survey, the same datasets and qualitative integrated evaluation methods were also adopted. By referring to the SL190–2007: Standard for Classification and Gradation of Soil Erosion (Table 3) on the classification of erosion, the study area was divided into six zones with different slope gradient zones and five categories with different vegetation coverage range (Figure 3) to assess the soil erosion intensity in Yunnan in 2010 with assistance of data on soil types and landscape characteristics [12].

For vegetation cover, woodland and grassland showed similar pattern in distribution as the 45–60%, 30–45% and 60–75% categories were the top three dominant classes, the area percentage for woodland in these classes are 46.52%, 31.25% and 16.03%, and the percentage for grassland are 45.13%, 29.91% and 17.62%, respectively. As can be seen in Figure 3a, woodland and grassland with lower vegetation cover were mainly distributed in the highlands in the northwestern Yunnan. The area with slope <5° accounts for 28.60% of the total land area, slope gradient of 5–8°, 8–15°, 15–25°, 25–35° and >35° representing 7.12%, 22.30%, 27.54%, 11.48% and 2.97% of the total land area, respectively.

Table 3. Standards for the classification and gradation of soil erosion intensity levels.

Land Use Types	Vegetation Cover	Slope Gradient					
		<5°	5–8°	8–15°	15–25°	25–35°	>35°
Non-cultivation	>75%	Slight	Slight	Slight	Slight	Slight	Slight
	60–75%	Slight	Light	Light	Light	Moderate	Moderate
	45–60%	Slight	Light	Light	Moderate	Moderate	Intensive
	30–45%	Slight	Light	Moderate	Moderate	Intensive	Severe
	<30%	Slight	Moderate	Moderate	Intensive	Severe	Extreme
Slope-cultivation	–	Slight	Light	Moderate	Intensive	Severe	Extreme

Note: Relationships between soil erosion intensities and rates are: Slight (<5 $t \cdot ha^{-1} \cdot yr^{-1}$), light (5–25 $t \cdot ha^{-1} \cdot yr^{-1}$), moderate (25–50 $t \cdot ha^{-1} \cdot yr^{-1}$), intensive (50–80 $t \cdot ha^{-1} \cdot yr^{-1}$), severe (80–150 $t \cdot ha^{-1} \cdot yr^{-1}$) and extreme (>150 $t \cdot ha^{-1} \cdot yr^{-1}$).

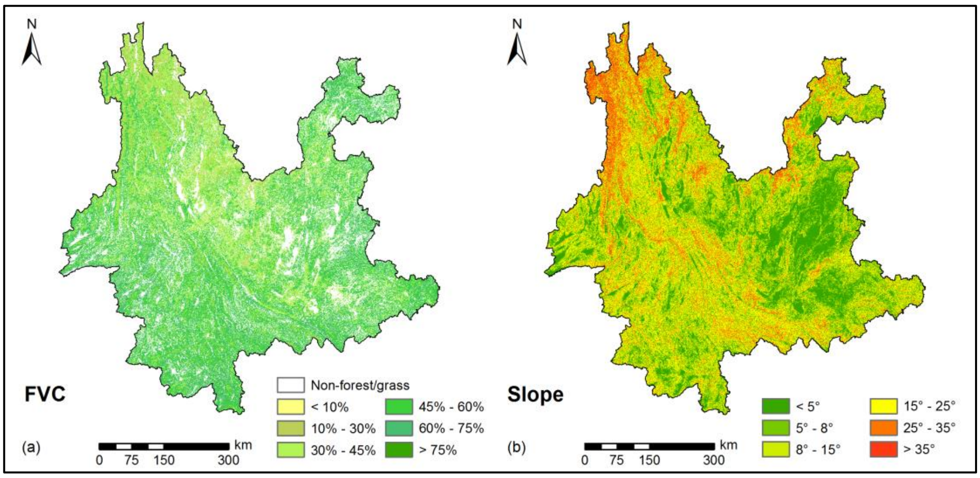

Figure 3. (**a**) Vegetation fraction cover of Yunnan in 2010; (**b**) Slope gradient of Yunnan in 2010.

3. Results

3.1. Spatial Distribution of Soil Erosion Factors of CSLE

Figure 4a reveals the spatial distribution of annual average rainfall erosivity of Yunnan for 1981-2010. The *R* values were found to range from 794.76 to 8399.38 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$ and with an average of 3415.21 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$. The spatial distribution of the *R* values showed a significant decreasing trend from the southeast to the northwest. Lower *R* values were mainly distributed in the northern tip, while higher *R* values were primarily distributed in the southern portion of the Yunnan. For most areas, the *R* values were between 2000 to 4000 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$.

The map of *K-factor* showed in Figure 4b was calculated by using the USLE method, and the average *K* value of the study area was 0.0286 $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$, varying from 0 to 0.0484 $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$, and then the *K* factor was adjusted by using unit plot and cropland plot data throughout Yunnan. For the six major basins, the *K* values of the Pearl River Basin were obviously lower than those of the other five basins. Higher *K* values mostly occur in the northwest portion of Yunnan.

The *LS-factors* in Figure 4c vary from 0 to 59.19, with a mean value of 9.25. Areas with higher *LS* values were generally located in western mountainous area and areas with lower *LS* values mainly located in the Pearl River Basin with relatively gentle slopes.

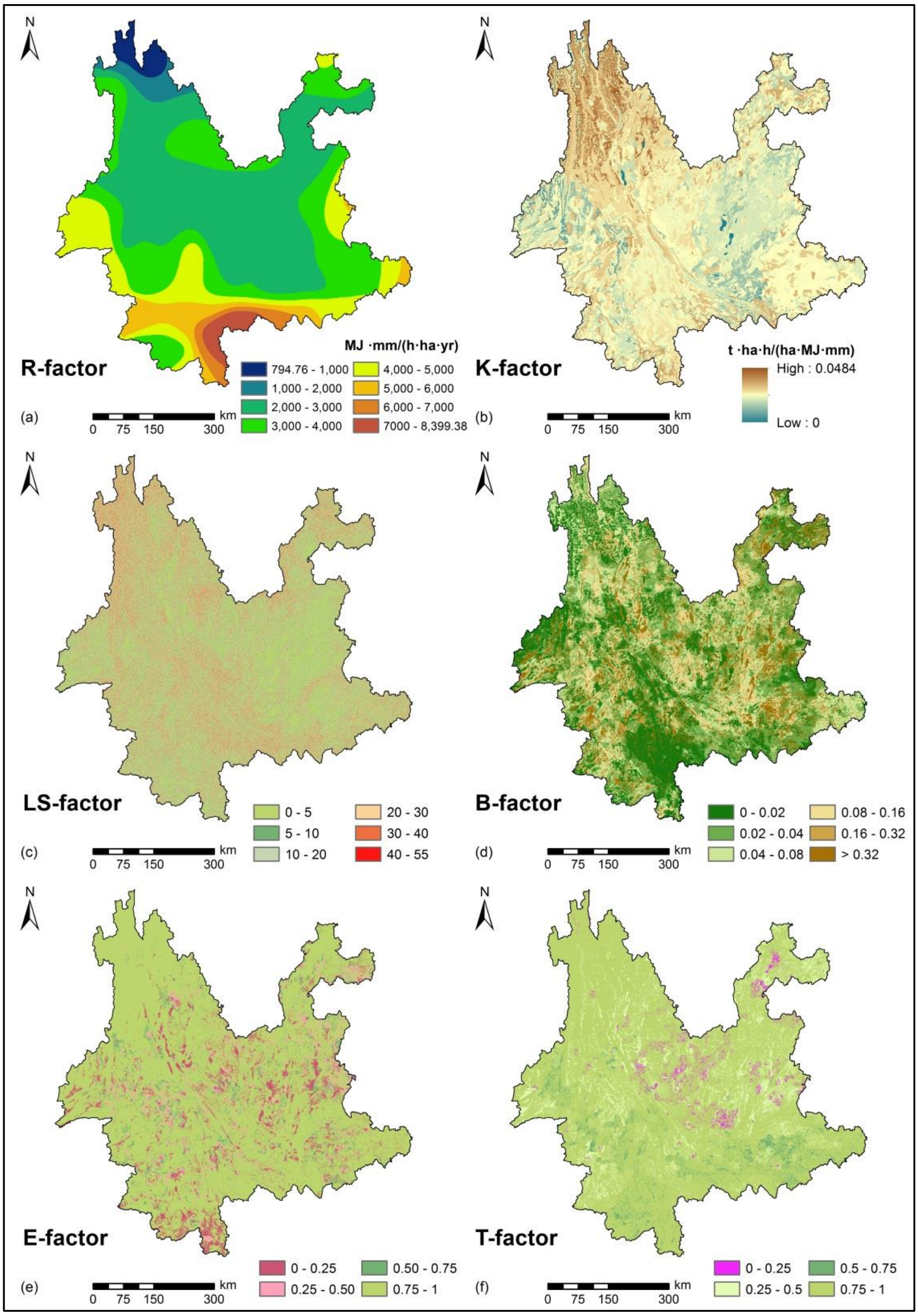

Figure 4. Spatial distribution of soil erosion factors in the Chinese Soil Loss Equation (CSLE) model in Yunnan. (**a**) Rainfall erosivity; (**b**) Soil erodibility; (**c**) Topographic factor; (**d**) vegetation cover factor; (**e**) Engineering factor; (**d**) Tillage factor.

The *B-factor* map in Figure 4d was produced using NDVI data. The *B* values in Yunnan vary from 0 to 1, with a mean value and standard deviation of 0.049 and 0.067, respectively. The lower *B* factor values were found in most of the study area, since the majority of the land was covered by forest and grass. Higher *B* factor values were only found in arable lands and artificial lands.

The maps of *ET-factors* in Figure 4e,f were prepared from the PSU data in the national survey and interpolated using land use datasets. Lower *ET values* were found in the central parts and moderate *ET values* were found in the northern parts, while higher ET values were mainly distributed in southern Yunnan. In other words, arable lands in these areas were treated with less effective soil conservation measures.

3.2. Spatial Distribution of Soil Erosion in Yunnan

The spatial pattern of soil erosion rate in Yunnan Province was revealed (Figure 5a) with the relevant parameters of the CSLE model modified as input layers under a geographic information system framework. Erosion rates were then classified into six intensity levels based on *SL190-2007* proposed by the Ministry of Water Resources of China. Results showed that 1.48×10^7 ha of land was suffering from erosion with a rate higher than the soil loss tolerance (T) of 5 $t \cdot ha^{-1} \cdot yr^{-1}$ in 2010, occupying 38.77% of the total land area in Yunnan. The average annual soil erosion rate of the province was found to be 12.46 $t \cdot ha^{-1} \cdot yr^{-1}$ and the total annual soil loss was about 0.47 Gt. Slight, light, moderate, intensive, severe and extreme erosion accounted for 61.23%, 28.32%, 5.30%, 1.98%, 1.77% and 1.39% of the total land area, respectively. As can be seen in Figure 5a, severe and extreme erosion mainly occurred in the agricultural areas in southern Yunnan, while most areas in central and northern Yunnan fell within the categories of slight and light erosion. The regional variation was significantly impacted by the variation in the annual rainfall erosivity, topographic factors, as well as soil conservation practices adopted in these regions.

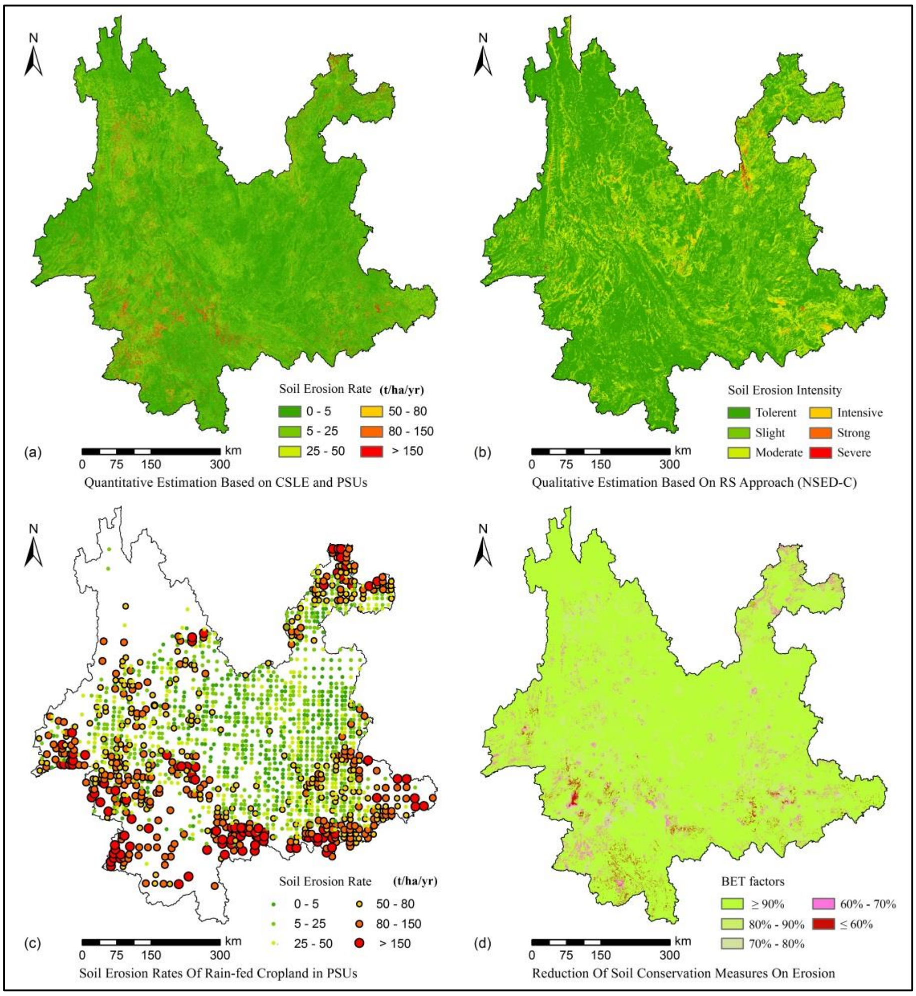

Figure 5. Spatial patterns of soil erosion, erosion intensities and effects of conservation measures. (**a**) Quantitative CSLE estimation; (**b**) Qualitative RS estimation; (**c**) Rain-fed cropland erosion rate in PSUs; (**d**) Effects of soil conservation measures.

The CSLE estimates in the study were consistent with the field-based assessment in PSUs. Data from 2010 NSES showed that out of 2871 PSUs in Yunnan, rain-fed cropland parcels were found within 1800 PSUs in the field investigation, the average soil erosion rates of rain-fed cropland in these PSUs were revealed in Figure 5c, which were calculated based on first hand on-site data with higher resolution (10 m) in the 2010NSES for each PSU [22]. Additionally, the effect of soil conservation measures on erosion reduction is also presented in Figure 5d. The distribution of soil erosion and soil conservation measures adopted showed a close negative correlation. For most areas, the combined soil conservation measures (*BET*) contributed to a total of 80% reduction on erosion, while the lower *BET-factors* generally resulted in severe and extreme erosion intensities. Policymakers should promote anti-erosion measures by financing land management practices, such as terracing, contour cropping, plastic film mulching and furrow planting, which have been proved to be effective on soil erosion reduction in central and northeastern Yunnan [52].

For the six major basins in Yunnan, higher soil erosion intensities generally occurred in the lower reaches of the rivers as compared to the upper reaches, this is mainly because the higher rainfall erosivity and a larger proportion of rain-fed cropland existed in the downstream areas. The erosion ratios (percentage of area eroded with a higher rate than T in the total land) of the six basins were sorted in descending order as follows: The Mekong > the Salween > the Red > the Yangtze > the Irrawaddy > the Pearl. Results in Table 4 demonstrated that the Mekong River Basin, the Salween River Basin and the Red River Basin were suffering serious soil erosion problems in terms of mean soil erosion rates and soil erosion ratio, while soil erosion of the Pearl River Basin and the Irrawaddy Basin were much optimistic.

Table 4. Soil erosion in the six major river basins in Yunnan.

Basin	Area (10^4 ha)	Area %	>T (%)	SLR (t ha^{-1} yr^{-1})	SL (10^6 t yr^{-1})	% of TSL
Yangtze	1078.63	28.24%	37.28%	10.19	109.89	23.31%
Mekong	882.73	23.11%	42.83%	16.89	149.12	31.63%
Irrawaddy	187.10	4.90%	27.29%	9.22	17.26	3.66%
Salween	334.57	8.76%	45.55%	14.48	48.43	10.27%
Pearl	591.67	15.49%	31.44%	7.66	45.31	9.61%
Red	745.01	19.50%	41.80%	13.61	101.39	21.51%
Yunnan	3819.70	100%	38.77%	12.46	471.40	100%

Note: T, soil loss tolerance; SLR, soil loss rates; SL, soil loss; TSL, total sol loss.

3.3. Soil Erosion Variations under Different Land Use Types in Yunnan

A spatial analysis of soil loss rates by land use type using the major 2nd level NLUD-C land use classes was made. Results showed that most of the soil erosion took place on rain-fed cropland. The average soil erosion rate for rain-fed cropland (47.69 t·ha^{-1}·yr^{-1}) was about four times of the overall soil erosion rate (12.46 t·ha^{-1}·yr^{-1}) in Yunnan. Only 37.56% of the rain-fed cropland in Yunnan was being eroded with acceptable erosion rate and 64.24% suffered a soil loss rate higher than T. For the whole province, light, moderate, intensive, severe and extreme erosion accounted for 21.69% (111.51 × 10^4 ha), 13.72% (70.55 × 10^4 ha), 9.44% (48.53 × 10^4 ha), 10.48% (53.89 × 10^4 ha) and 8.91% (45.79 × 10^4 ha) of the rain-fed cropland area in 2010. Consequently, rain-fed cropland accounted for 52.06% of the total soil loss from all land use types, while it only took up 13.47% of the total land area in 2010. Grassland and woodland also suffered from serious erosion, 39.20% of grassland and 36.71% of woodland in Yunnan were being eroded. Although the erosion rates of woodland and grassland were much lower compared to those from rain-fed cropland, erosion from them should not be underestimated. The annual soil loss from woodland accounted for 35.65% of the total soil loss as it covered 57.64% of the land in Yunnan. Grassland covered 22.55% of the land area and contributed to 11.71% of the total soil loss. To some extent, water bodies, built-up areas and unused land were practically non-erodible, contributing to 0.39% of the total soil loss with 2.01% of the total land area.

The average soil loss rates for the major 2nd-level NLUD-C land use classes and corresponding share of soil loss were listed in Table 5. Due to the higher vegetation cover and as a consequence, lower B values, the mean soil erosion rates for forest (4.46 t·ha^{-1}·yr^{-1}) and dense grass (5.80 t·ha^{-1}·yr^{-1}) were acceptable. Areas covered by paddy, forest and dense grass showed relatively lower erosion ratio compare to other 2nd-level types. Moderate grass and shrub had a similar erosion ratio (about 42%) and moderate erosion rates among all 2nd-level types. Erosion on sparse woods and sparse grass were noticeable, particularly sparse woods that distributed in high attitudes. Despite the low B-factor, sparse woods were characterized with soil erosion rate (14.53 t·ha^{-1}·yr^{-1}) and soil loss contribution ratio (15.39%) only ranked behind rain-fed cropland. The major reason behind is many of the sloping orchards and tea gardens (classed in sparse woods in the NLUD-C classification) resemble the rain-fed cropland in terms of management and cultivation, resulting in serious erosion problems. Meanwhile, this is the most uncertain land-cover class due to the ambiguity between the NLUD-C land cover classification and the field survey. Anti-erosion measures should be promoted to sparse woods, especially sloping gardens as the large proportion in Yunnan and the considerable soil loss yielded. The CSLE estimates under different land use types compare well with local measurements from Yang et al. [53] under experimental plots.

Table 5. Mean soil loss rates for different land uses and corresponding shares of soil loss.

Land Use	Area (10^4 ha)	Area %	> T (%)	SLR (t·ha^{-1}·yr^{-1})	SL (10^4 t·yr^{-1})	% of TSL
Paddy	165.44	4.33%	1.58%	0.54	88.7	0.19%
Rain-fed cropland	514.54	13.47%	64.24%	47.69	24539.2	52.06%
Forest	849.69	22.24%	26.52%	4.46	3792.0	8.04%
Shrub	852.94	22.33%	42.08%	6.75	5760.4	12.22%
Sparse woods	499.22	13.07%	44.85%	14.53	7255.0	15.39%
Dense grass	540.55	14.15%	36.77%	5.80	3134.4	6.65%
Moderate grass	295.48	7.74%	42.40%	7.16	2115.2	4.49%
Sparse grass	25.19	0.66%	53.98%	10.77	271.4	0.58%
Water Bodies	27.90	0.73%	0	0	0	0
Built-up land	28.20	0.74%	3.81%	1.18	33.2	0.07%
Unused land	20.56	0.54%	4.71%	7.35	151.2	0.32%

Note: The 11 land-use types listed above are summarized based on the classification systems prescribed in the NLUD-C and area proportion. Arable land, woodland and grassland are major 1st-level types and divided into 2nd-level types as they occupy about 98% of the province. Arable land consists of paddy and rain-fed cropland; Woodland consists of forest, shrub and sparse woods; Grasslands includes dense grass, moderate grass and sparse grass; water surface, built-up land and unused land remain 1st-level types as the low area proportion in Yunnan. T, soil loss tolerance; SLR, soil loss rates; SL, soil loss; TSL, total sol loss.

Significant regional differences of rain-fed cropland in soil erosion rates were also found among the six major river basins, rain-fed croplands in the basins of the Mekong, the Salween, the Red and the Irrawaddy showed obviously higher rates than those of the other two basins, with an average annual soil erosion rate of 69.79, 53.78, 54.25 and 52.20 t·ha^{-1}·yr^{-1} respectively, while rain-fed cropland in the Yangtze River Basin and the Pearl River Basin experienced respective erosion rate of 35.06 t·ha^{-1}·yr^{-1} and 23.42 t·ha^{-1}·yr^{-1}. This is mostly due to the high rainfall intensity and the steep slopes for the former basins, while special attention was given to slope cropland in the lower reaches of the Yangtze, which has been listed as the key priority for ecological construction and soil conservation for three decades, rain-fed cropland of the Pearl River Basin experiences relative gentle slopes, lower soil erodibility and complete soil conservation systems. For all the basins, rain-fed cropland in the downstream areas generally suffers a higher soil loss rate than the upstream areas.

3.4. Comparison of Predicted Soil Loss Rates with the Estimates of Qualitative RS Method

Figure 5b shows the estimates in the National Soil Erosion Database of China (NSED-C) using qualitative integrated evaluation method (hereinafter referred to as the RS method). The qualitative RS method uses indicators of the slope, vegetation coverage of different land uses to grade the soil erosion intensity. The spatial pattern of soil erosion mapped by means of the CSLE method and the RS method have certain similarities and differences in the present study. Both mapping methods resulted in lower erosion rates in arable lands in the central portion of the study area, which can lead to greater attention given soil and water conservation measures adopted in these areas. Because of the difference in soil erosion affecting factors considered, erosion hot spots identified in the southeast and southwest by the CSLE method were experiencing much more severe erosion than those identified by the RS method. Estimates of the qualitative RS method showed that the soil erosion ratio of the province in 2010 was 36.72%, light, moderate, intensive, severe and extreme erosion accounted for 20.65%, 13.78%, 2.14%, 0.11% and 0.05% of the province, respectively. The erosion ratios for the major 2nd-level land use types were sorted in descending order as follows: Rain-fed cropland (64.78%) > moderate grass (59.62%) > dense grass (57.24%) > sparse grass (40.60%) > sparse woods (31.56%) > paddy (30.43%) > shrub (29.82%) > forest (10.97%).

Figure 6 shows the 1st-level land use composition of each soil erosion intensity level for the two estimates using different approaches. Woodland appeared to be the most dominant land type in relative lower intensities (slight, light and moderate) for both estimates. As can be seen in Figure 6a, the proportions of woodland and grassland showed a declining trend as the erosion intensity increases for CSLE estimates. The situation is totally opposite for arable land, which contributed to 86.09% of the extreme erosion area, 79.61% of the severe erosion area, 64.08% of the intensive erosion area. For the quantitative method, severe and extreme erosion mostly occurred in rain-fed cropland and sparse woods. However, for the qualitative estimates, a similar trend (Figure 6b) as arable land in the former situation was found on grassland, which indicated that grassland in Yunnan was being eroded with higher erosion intensity levels than other types.

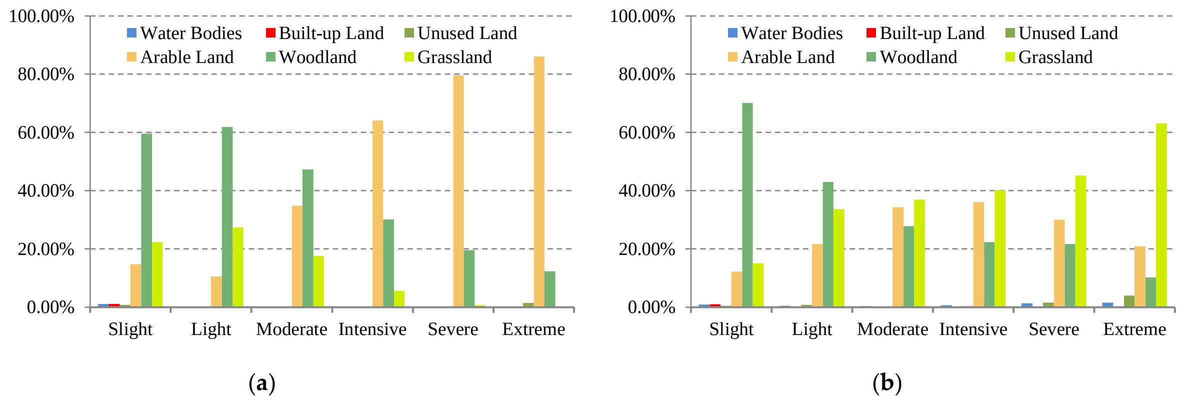

Figure 6. Land use composition of each soil erosion intensity for the two estimates: (**a**). Land use composition of each erosion intensity (CSLE); (**b**). Land use composition of each erosion intensity (RS).

The difference was analyzed by subtracting the CSLE estimates from the qualitative RS method estimates. Of the total land, 47.72% showed no difference in soil erosion intensity for the two results. Land with differences of 1 erosion intensity level and 2 erosion intensity levels accounted for 35.54% and 12.09%, respectively. Differences of three or more erosion intensity levels accounted for 4.65%. For the six first-level land use types, the difference ratio of arable land (64.15%) between the two estimates was the highest, followed by grassland (63.74%) and woodland (45.09%), built-up land, unused land and water bodies generally show a difference ratio less than 20%.

These differences can be explained as following specific reasons. First, the qualitative RS method applied in NSED-C uses DEM of 100 m cell size to generate topographic index at the national scale, which was very coarse for mountainous areas like Yunnan and will inevitably cause a decline in slope gradient and arable land erosion, since slope gradient is the only basis to grade erosion intensity for arable land in the RS method. Besides, vegetation indexes derived from the qualitative RS method only represent the vegetation cover growing season (from day 193 to day 225), which cannot reflect the seasonal variation for both vegetation and rainfall and may lead to uncertainties for land use types with a permanent cover. These are the major causes directly related to the underestimation of soil erosion and priority areas identified by the RS method compared with the CSLE estimates. Lastly, many sloping gardens (classified as sparse woods) in Yunnan, especially tea gardens, resemble arable land in terms of cultivation pattern, and suffer from the same serious soil erosion as the slope cropland [54]. But the qualitative method treats the gardens as forests in terms of intensity grading, which leads to lower intensity levels than the CSLE method. For grassland erosion, the qualitative estimates were overestimated compared to the quantitative CSLE estimates. This is mainly because grasslands mostly located in highlands with steep slopes in the northwest portion, whereas rainfall erosivity appeared to be the lowest in the province, while rainfall was not taken into account in the qualitative RS method.

3.5. Policy Interventions on Rain-Fed Cropland Soil Erosion Reduction

The spatial pattern of rain-fed cropland erosion rate generally describes the outline of the actual erosion situation in Yunnan. In order to evaluate the effects of policy interventions on soil erosion reduction, a cross-comparison was made to compare the CSLE estimates in the present study with previous local assessments conducted by Yang et al. [55]. We reclassified the erosion grades and divided the province into five agricultural regions according to their study and statistics on soil erosion rate were made at a county level. Figure 7a shows the spatial distribution of soil erosion rate from rain-fed cropland in 2006, which was produced using a method incorporating local soil loss equation, measurements under experimental plots and a provincial land use investigation [55]. Figure 7b presents the spatial distribution of soil erosion rate from rain-fed cropland in this study in 2010. The two field-based quantitative approaches to assessing soil erosion related well with each other in terms of the spatial pattern of erosion rate. The most significant sheet and rill erosion hot spots were located in the SW region for both estimates, soil loss from this region accounted for 37.1% and 48.67% of the total soil loss for each estimate, due to a large proportion of rain-fed cropland in this region. For most areas, soil erosion from rain-fed cropland showed a significant declining trend from 2006 to 2010, especially in the northeast and central portions of the province. Of the counties in the province, 44.8% (56 out of 125) showed a decline in erosion grades in 2010 compared to 2006, 36% (45 out of 125) of the counties remains the same erosion grades for the two estimates and the remaining 19.2% (24 out of 125) of the counties shows an increase in erosion grades, mostly in the southern areas. For the whole province, the average annual sheet and rill erosion rate on rain-fed cropland fell from 59.65 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$ in 2006 to $t{\cdot}ha^{-1}{\cdot}yr^{-1}$ in 2010, with a 20% decrease. For the five agricultural regions, erosion rate on rain-fed cropland has dramatically changed in the NE (from 78.84 to 45.37 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$), NW (from 70.41 to 57.80 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$), Central (from 38.91 to 21.01 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$) and SE (from 56.58 to 53.86 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$) regions, while only in SW Region, the soil erosion rate remains the same level (68.94 to 69.00 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$). As a result, annual soil loss from rain-fed cropland has decreased from 3.63×10^8 t in 2006 to 2.46×10^8 t in the present study, with a 32% decrease.

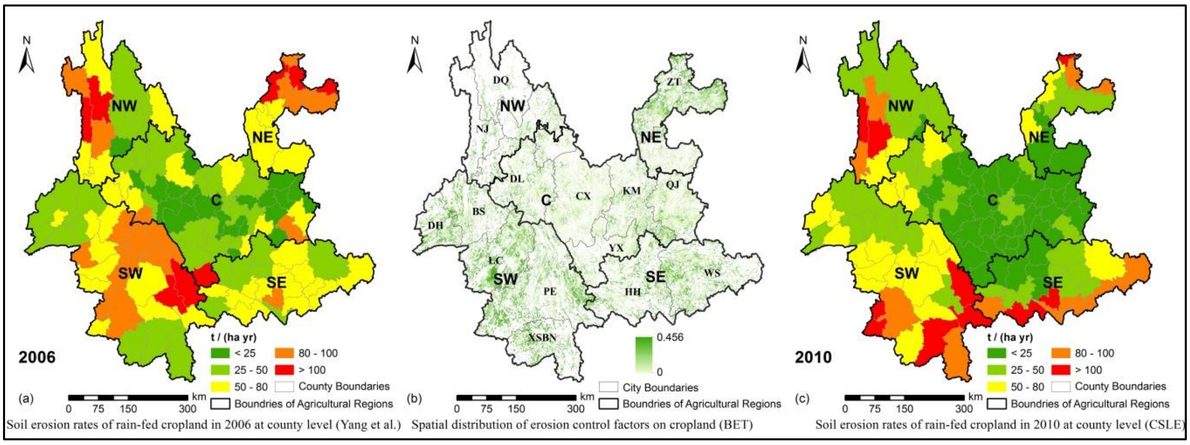

Figure 7. Spatial changes of cropland erosion at county level in Yunnan. (**a**) Rain-fed cropland erosion rate in 2006; Effects of erosion control measures; (**c**) Rain-fed cropland erosion rate in 2010.

The reduction in soil erosion rate can be attributed to two factors: Improved conservation practice on cropland and conversion of slope cropland (> 5°) to forest or grass. During the last decade, policies, such as the Grain-for-Green Program (GFGP) [56,57], a project of returning steep slope cropland to forest/grass, policy of transforming slope land into the terraced field and other local soil conservation projects have dramatically improved the soil conservation benefits in the province. Figure 7b presents the spatial pattern of soil erosion control measure effects for a combination of vegetation cover practice (*B-factor*), engineering practice (*E-factor*) and tillage practice (*T-factor*) on cropland in 2010. The average erosion control factors (*BET*) for cropland of the province was 0.174, which means that soil conservation measures adopted in cropland have reduced the total soil loss by 82.6% compared to the potential soil erosion risk. For the five agricultural regions, the respective values for the NE, NW, SW, SE and Central regions were 0.189, 0.199, 0.233, 0.196 and 0.101. As can be seen, the central region showed the lowest value which can be explained as complete conservation systems and the largest portion of paddy existed in this area. Meanwhile, the NE agricultural region showed the second lowest value, due to the special attention given to slope cropland in the Yangtze River Basin, which has been listed as one of the key priorities for soil conservation and ecological construction in the country. However, according to Yang's earlier studies [58], the NE region was known for extreme soil erosion before, since slope cropland accounted for 94.52% of the total cropland in the area and 87.87% of these slope cropland was absent of any soil and water conservation measures. Moreover, only about 20% of the land in this area was covered with forest and grass before.

The other major reason contributed to the decline was the changes in slope cropland areas. It is reported that about 2.4×10^5 km^2 of slope farmland existed in China, which causes a total soil loss of about 1.42 billion tons each year and accounts for nearly one-third of the total soil loss of the country [59]. Previous study [60] has confirmed that cropland is the most important source of soil loss in China and erosion rates from slope cropland can be tens to hundreds of times of those from grassland. As can be seen in Figure 8, the slope cropland area in Yunnan has fellen from 410×10^4 ha in 1997 to 377.1×10^4 ha in 2010, with an 8% decrease. The decrease mainly distributed in QJ and KM (The Central region), WS and HH (the SE region) and ZT (the NE region). The year 1997 was selected as a reference because it was the closest year that Yunnan conducted a detailed land use survey before the Grain–for–Green Program (GFGP) started in 1999.

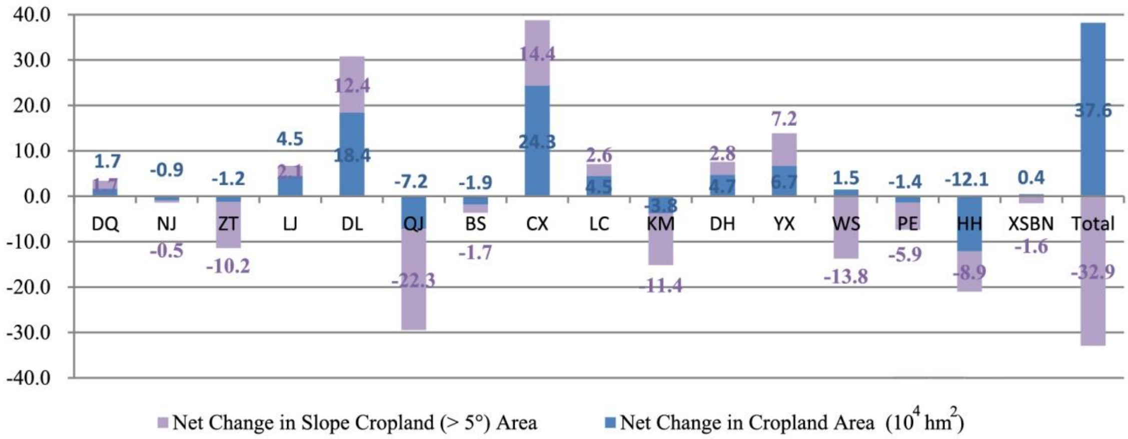

Figure 8. Changes in cropland areas for the 16 municipal districts in Yunnan during 1997–2010.

However, the pressure from population growth on remaining land resources is very high, to meet the greater demand for food, the cropland area showed a remarkable increasing trend, from 642 × 10^4 ha in 1997 to 679.6 × 10^4 ha in 2010, with a 5.86% increase. The increased slope cropland area mostly concentrated in CX, DL and YX of the Central region. As can be seen in Table 6, the relative lower erosion control factors values in these districts suggested that high soil conservation efficiency existed in cropland. However, even the slope land in the Central region showed the lowest erosion rate among the five regions, it was still several times above the tolerant erosion rate. Moreover, LC and DH of the SW Region, DQ and NJ of the NW Region were also involved in increased slope cropland, which should not be neglected because of the relative higher erosion control factors (lower erosion control efficiency) in these areas. Policy interventions have reduced the slope cropland proportion remarkably, still, only 5 out of 16 municipal districts with a slope land percentage lower than 50% and a total of 53.01 × 10^4 ha of cropland in Yunnan were still located on slopes >25°. Since about 84% of the province was classed as mountainous landscape and the plain areas already fully utilized for agriculture, which will inevitably lead to the expansion and creation of new cropland onto steep slopes. To further reduce soil erosion on cropland and thereby mitigate the environmental and social implications, policy options, such as technical assistance and education should be available to induce farmers to implement soil conservation measures.

Table 6. Cropland erosion control effects and slope cropland percentage for the 16 districts in 2010.

District	BET	SC % (1997)	SC % (2010)	District	BET	SC % (1997)	SC % (2000)
DQ	0.217	71%	77%	LC	0.237	77%	75%
NJ	0.248	88%	92%	KM	0.127	59%	37%
ZT	0.212	86%	72%	DH	0.200	35%	40%
LJ	0.144	67%	63%	YX	0.090	43%	58%
DL	0.141	50%	56%	WS	0.190	65%	43%
QJ	0.093	59%	32%	PE	0.248	77%	71%
BS	0.175	59%	57%	HH	0.202	55%	50%
CX	0.065	52%	55%	XSBN	0.295	48%	39%
Yunnan	0.174	64%	55%	–	–	–	–

Note: SC%, slope cropland percentage.

4. Discussion

The 2010 National Soil Erosion Survey was the first attempt to acquire comprehensive soil erosion data in the field for the whole country in China's history. The year 2010 was selected as the reference year in the present study largely depend on the inter-agency field-based data collection, especially in quantifying the effects of soil conservation measures, the update of National Land Use/Cover

Database of China was also conducted in this year. It should be noted that the CSLE model was selected because of the data availability and its simplicity. The model has been well studied and widely applied at different scales to estimate soil erosion plan erosion control for different landscapes in China. When comparing the CSLE model with the other erosion empirical methods and qualitative approaches in China, the former gives much more detailed information on erosion rate and soil conservation measures. In other words, CSLE method reflects the actual situation better than the qualitative method in this study, due to the field-based survey. The model also uses secondary data freely available under a Geographic Information System framework as an alternative approach. For the decision makers, the predictable and reliable soil erosion rate is of the utmost importance. However, it would be unwise to use the CSLE model if sufficient input data are not available, since data availability maybe the most important concern in determining the approach selected.

Several problems arise when applying quantitative models at a regional scale, or larger scales. First, a model-based approach implies uncertainties in the process of calculation of the relevant parameters, which is common in all model-based approaches. Additionally, the empirical models only used to predict long term annual soil loss, gully erosion, sediment and landslide are not taken into account. Nevertheless, uncertainties also exist in the qualitative RS method, since remote sensing is a process of reflecting earth surface information through electromagnetic waves, due to the uncertainty of understanding in identifying and interpretation from different people, subjective errors will occur and affect the extraction of information, especially for mountainous areas with complex topography situations. Therefore, in selecting the suitable method for mapping soil erosion, decision makers should consider both the purpose in question and the similarities and differences in spatial patterns of the conservation priority areas that may arise from using different methods. The cross-comparison between the two major approaches (CSLE and RS methods) could identify regions and land use types that further study is needed. The CSLE method provides a better understanding of the erosion situation in Yunnan compared to qualitative RS method, as it takes account into two important factors, the soil conservation practices and the seasonal variability of vegetation and rainfall. In this study, we also compared the CSLE estimates with local assessments based on plot measurements provided credible information for comparison. However, the major limitation of soil erosion estimated at a county level is soil erosion variation within each county is not clear. Despite the affecting factors of rainfall erosivity, soil erodibility and human activities can be similar within the same county, but the topography conditions may vary greatly, which leads to more uncertainty.

The high erosion rate and erosion ratio of sparse woods are mainly because the large area of sloping gardens exist in Yunnan, especially tea gardens in the southern portion, which suffer from almost the same serious soil erosion as arable lands do. Southern Yunnan is known for high temperature and intensive rainfall in the summer, but it is also where tea gardens and orchards concentrated. Based on our field investigation, most of these gardens are planted same as row crops, besides, since many slope croplands in the province have been converted into fruit garden for farmers, in order to gain more income, some farmers still use the same cultivation pattern as arable land. According to the study [54] of local experts in 2004, the percentage of the soil erosion area in the garden and forest land even reached 40.92% and 36.24% respectively. Moreover, the average soil erosion rate for garden and forest land reached 22.01 and 7.07 $t \cdot ha^{-1} \cdot y^{-1}$, which were much higher than the respective value of 14.53 and 4.46 $t \cdot ha^{-1} \cdot y^{-1}$ in the present study. The interpretation of Landsat OLI images showed that very high vegetation cover existed in woodlands, but little ground cover actually found in the field survey. Serious erosion also occurred in the purely man-made forests, open forests and young forests in the province.

5. Conclusions

Quantitative soil loss assessment is one of the important scientific foundations for land resources management and soil conservation planning, especially for mountainous areas. Largely based on the latest 2010 National Soil erosion Survey, 2010 National Land Use Update, as well as the national soil investigation and other data sources, a quantitative pixel-based estimation was made using the CSLE model to produce the soil erosion map of Yunnan Province at 30 m resolution for the reference year of 2010. The spatial pattern of soil erosion, erosion variation under different land use types and the impact of soil conservation practices were well analyzed. The erosion hot spots were identified and compared with the qualitative results from NSED-C. Meanwhile, a comparison between the 2010 CSLE estimates and local assessments in 2006 at a county level was made to reveal the soil erosion change. Soil erosion rates in the five agricultural regions, six major river basins and 11 major land use types in Yunnan Province were estimated and clarified. Lastly, differences and uncertainties for the soil erosion assessing approaches were discussed. The main findings are summarized as follows:

(1) Yunnan has a mean annual soil loss rate of 12.46 $t \cdot ha^{-1} \cdot y^{-1}$ and 38.77% of the total land was being eroded at a rate higher than the soil loss tolerance. As a result, the total annual soil loss of the province was estimated at around 0.47 Gt. The results of CSLE compared well with national data reported in the 2010 national soil erosion survey. Extreme and severe erosion were mostly found in the southern agricultural areas, while the central and the northern potions mostly fell within the light and moderate erosion categories. For the six river basins, the downstream areas generally suffered more serious erosion than the upstream areas, which can be attributed to two reasons, the large portion of cropland in the downstream areas and higher rainfall erosivity, especially for the lower reaches of the Mekong, the Salween and the Red rivers. CSLE was found to be a suitable approach for estimating soil loss at the regional scale for the mountainous region

(2) Spatial analysis by land use types demonstrated that rain-fed cropland suffered the most severe erosion in 2010, with a mean erosion rate of 47.69 $t \cdot ha^{-1} \cdot y^{-1}$ and an erosion ratio of 64.24%. Soil loss from rain-fed cropland accounted for more than 52% of the total soil loss from all land use types, while rain-fed cropland only occupied 13.47% of the total land area. Special attention should be given to the sparse woodland and the 8.91% (about 45.79 $\times 10^4$ ha) of rain-fed cropland that were being eroded with irreversible rates of soil loss (>150 $t \cdot ha^{-1} \cdot y^{-1}$). Meanwhile, policymakers should not underestimate soil erosion from land with a permanent vegetation cover in Yunnan, although the soil loss rates for most woodland and grassland were not comparable with those on rain-fed cropland, still, about 39.20% of the grassland and 36.71% of the woodland had unsustainable mean soil loss rates > 5 $t \cdot ha^{-1} \cdot y^{-1}$. Soil erosion from sparse woods (followed only after rain-fed cropland) was noticeable. This is mainly because many slope horticultural lands existed in the province, especially tea gardens and slope fruit gardens, which basically used the same cultivation pattern as farmland.

(3) The comparisons between the CSLE estimates and the NSED-C estimates indicated that soil erosion in rain-fed cropland, sparse woods and grassland distributed in the highlands need further study and the estimates of NSED-C should be interpreted carefully. Compared with local assessments and measurements under experimental plots in literature, the SW region still suffered from serious erosion problem while the other four regions showed a remarkable decline in erosion, especially for the NE region. It is estimated that policy interventions have reduced soil erosion on rain-fed cropland by 20% in erosion rate and 32% in total soil loss compared to the local estimates in 2006. However, even with this reduction, soil erosion rate from rain-fed cropland is still several times above the acceptable rate. As the pressure of population and urban growth keeps driving rain-fed cropland onto increasingly steep slopes, effective soil remediation measures and soil conservation are necessary for most areas to maintain sustainable agriculture, since more than half of the districts in the province still had a slope cropland ratio greater than 50%. Besides, Yunnan is still the province with the largest slope cropland area in the country.

(4) The major advantage of this study is we integrated the field-based investigation of soil conservation measures into soil loss estimation. Although the interpretation of aerial photographs allows the detection of many conservation measures, so far there have been few studies on the application. Meanwhile, time series remote sensing data and meteorological satellite should also be incorporated in erosion assessments to save the high time and labor requirement to make a field survey. Therefore, close collaboration between the field-based erosion scientists and the remote

sensing community is required for the further erosion assessment at a regional scale, and larger scales. CSLE was found to be a suitable approach for estimating soil loss at the regional scale for the mountainous region, it is hoped that the results of this study will be of interest to those involved in the management of soil resources in Yunnan.

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