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Soil erosion rates assessed by RUSLE and PESERA for a Chinese Loess Plateau catchment under land-cover changes

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Abstract

On the Chinese Loess Plateau, soil erosion models are often employed to predict erosion rates and responses to land use/cover changes (LUCCs). Previous Loess Plateau studies employed individual models with specific emphases but model comparisons have not been undertaken so the relative performance of different models is not known. In this study we employed two extensively applied models (RUSLE and PESERA) to investigate the impact of LUCCs during 1990-2000 and 2000-2011 on soil erosion rates for a typical Loess Plateau catchment (i.e. Huangfuchuan), and compared their modelling results. Land-cover patterns for 1990, 2000 and 2011 were derived from Landsat images. The catchment was dominated by grassland (over 70%) and experienced considerable LUCCs: vegetation coverage increased from 38.3 % in 1990 to 48.7% in 2011. Modelling results suggested that mean soil erosion rates of the catchment increased under the 1990-2000 LUCC and decreased under the 2000-2011 LUCC. Sandy land and scrubland were found to suffer from most severe soil erosion and thus should be the focus of future conservation work. Mean soil erosion rates on steep slopes (i.e. >25°) were predicted to increase under the 2000-2011 LUCC, implying that further work is still needed to study soil erosion processes and their conservation on steep slopes. Model comparisons showed that RUSLE predictions were higher than PESERA predictions for most area (particularly for steep slopes), and the former were generally closer than the latter to check-dam sediment yield measurements. RUSLE and PESERA results were not linearly correlated, possibly due to differences in their underlying principles and their sensitivity to crucial parameters - RUSLE is more sensitive to slope gradients while PESERA is more sensitive to vegetation coverage. PESERA needs improvement to better account for steep slope erosion processes on the Loess Plateau, while RUSLE needs improvement in the description of vegetation effects.

Key words

Dryland; land degradation; erosion; soil conservation; multi-model assessment; model comparison

Introduction

Soil erosion is globally widespread (Oldeman, 1994, Yang et al., 2003, Wu and Chen, 2012, Borelli et al., 2017), resulting in various environmental and socio-economic problems, including reduced soil depth and soil organic matter (Pimentel, 2006), non-point pollution and reduced agricultural production (Wang et al., 2006b, Wu and Liu, 2012), degradation of river channels and downstream riverbeds (Tian et al., 2015), and exacerbated rural poverty (Wang et al., 2015). The Chinese Loess Plateau has been recognized as the most severely eroded area in the world (Shi and Shao, 2000, Tsunekawa et al., 2014, Sun et al., in press). Since the 1970s, large-scale soil and water conservation measures, including ecological restoration programs beginning in 1999 (i.e. the 'Grain-for-Green' project), have been implemented on the Plateau (Jiao et al., 2016, Wang et al., 2011, Sun et al., 2020), greatly altering the land use/cover pattern (Zhou et al., 2016). It has therefore become important to assess the impact of land-use changes and land-cover changes (LUCCs) on Loess Plateau soil erosion rates for the optimization of spatially-targeted and sustainable land management and rehabilitation strategies. Soil erosion models are vital in fulfilling the above research need over large landscape systems because they provide analyses of different scenarios, including future land management or climate effects. These models also avoid unfeasible labour and economic inputs required by traditional experimental catchment manipulations or very detailed monitoring (Wainwright and Mulligan, 2013), although field data is usually extremely helpful for model validation.

Over thirty soil erosion models have been employed in previous studies to assess soil erosion rates and/or their responses to LUCCs on the Loess Plateau (Li et al., 2017c). These studies employed individual soil erosion models (e.g. Li et al., 2010, Hessel et al., 2003, Wang et al., 2006a, Zuo et al., 2016, Sun et al., 2014, Feng et al., 2010, Yu et al., 2006, Qin et al., 2018), while no studies employed multiple soil erosion models to compare modelling results for the same catchment and time period. A model comparison study is not only helpful for understanding the relative performance of different models but also beneficial for showing whether there is a broad agreement or disagreement between model predictions. The former is important for the selection of an appropriate model while the latter is crucial to reduce uncertainties in predictions provided by individual models. Li et al. (2017c), for the first time, compared eleven soil erosion models that were previously used on the Loess Plateau and assessed model prediction accuracy, process representation, data and calibration requirements and potential application in scenario studies, and suggested research questions that each of the models can address. However, the eleven models were not compared based on datasets from exactly the same environmental conditions but from published work conducted at either different study sites or over different study periods.

Contemporary soil erosion models for the Loess Plateau are mainly catchment scale and event based, and few of them are capable of being applied over large areas (e.g. the whole of the Loess Plateau) on a long-term scale (e.g. 30 years) (Li et al., 2017c). A comparison of models that can be used for regional-scale studies is thus particularly meaningful for the selection and development of models for the Loess Plateau. Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991) and Pan-European Soil Erosion Risk Assessment (PESERA) (Kirkby et al., 2008) are two of the most extensively applied models capable of being applied at regional scales. They were both initially developed for estimating long-term soil erosion rates resulting from rill and interill soil erosion processes and can be applied over large scales through assuming the study site as a cascade of hillslopes. They are thus comparable in terms of spatial scale, temporal scale and spatial methodologies, making them suitable for a comparison (Panagos et al., 2014, Karydas et al., 2014). RUSLE and PESERA have previously been compared in studies investigating the impact of fires on soil erosion rates at a Mediterranean site (Karamesouti et al., 2016, Vieria et al., 2018) and 15 recently burned areas in northwestern Spain (Fernández and Vega, 2016). However, RUSLE and PESERA have not been compared for the Loess Plateau environment.

RUSLE is a systematic improvement of the classic empirical model USLE (Renard et al., 1991) and has been frequently applied over the Loess Plateau and widely considered as a robust model for erosion rate predictions through incorporating a steep slope factor calculation developed by Liu et al. (1994) (e.g. Tian et al., 2015, Fu et al., 2011, Sun et al., 2013, Sun et al., 2014, Zhao et al., 2015, Zhang et al., 2017). RUSLE erosion predictions have thus been used as a substitute for actual soil erosion rates at places without field measurements and regions where erosion data cannot be collected across the landscape (Fu et al., 2005, Tang et al., 2015, Zhao et al., 2015). PESERA, unlike RUSLE, is a process-based and spatially-distributed soil erosion model, which has not been applied to China yet (Li et al., 2016d). It explicitly describes the processes of hydrology, vegetation growth, erosion and their interactions (Li et al., 2016d), thus providing more detailed information than RUSLE on different components of soil erosion processes. PESERA has been widely applied and validated across Europe (e.g. Govers et al., 2003, Karamesouti et al., 2016, e.g. Licciardello et al., 2009, Tsara et al., 2005, Govers et al., 2003, Meusburger et al., 2010, Vieria et al., 2018). It has also been modified to take account of the impact of fires on erosion processes (Esteves et al., 2012) and freeze-thaw and desiccation sediment production processes in peatland soils (Li et al., 2017a, Li et al., 2017b, Li et al., 2016b, Li et al., 2016c).

The Huangfuchuan catchment (110.3°-111.2° E, 39.2°-39.9° N), located in the northern Loess Plateau, is an important catchment in the area and one of the most severely eroded, characterized by fragmented terrain and complex geomorphological units resulting from intensive hillslope and gully erosion (Li et al., 2016a, Tian et al., 2013, Zhao et al., 2015). Since the 1970s, a series of soil and water conservation measures (including the ‘Grain-for-Green’ project beginning in 1999) have been implemented in the Huangfuchuan catchment (Zhou et al., 2016). Previous studies have investigated the impact of LUCC on soil erosion and sediment yield from the catchment (e.g.Yu et al., 2006, Mu and Zhang, 2013, Zhao et al., 2013, Yu et al., 2014, Wang et al., 2014, Tian et al., 2015, Zuo et al., 2016, Li et al., 2016a, Wei and Jiao, 2017). However, most of these studies either focused on the changes in sediment yield at the catchment outlet or did not investigate the hillslope erosion rates since the ‘Grain-for-Green’ project (i.e. from 2000 onwards). The response of hillslope erosion rates to LUCCs before and after the ‘Grain-for-Green’ project has, to date, only been studied by Yu et al. (2014), in which USLE was employed to model soil erosion rates across the Huangfuchuan catchment under the land cover pattern of 1987, 1995, 2000 and 2007 through incorporating the steep slope factor developed by Liu et al. (1994). In fact, USLE and RUSLE have become the most commonly used models in the Huangfuchuan catchment (e.g. Yu et al., 2006, 2014, Tian et al., 2015). No studies have employed multiple spatial models to predict (and compare) soil erosion rates for the catchment.

Our study aimed to: (i) evaluate the impact of LUCCs before and after the ‘Grain-for-Green’ project on soil erosion rates for the Huangfuchuan catchment based on RUSLE and PESERA, and (ii) compare soil erosion rates modelled by PESERA and RUSLE. We firstly implemented RUSLE and PESERA to assess soil erosion rates for the Huangfuchuan catchment under land use/cover patterns for 1990, 2000 and 2011, then investigated the impact of LUCCs during 1990-2000 and 2000-2011 on soil erosion rates. Lastly, we compared RUSLE and PESERA predictions and compared them with sediment yield derived from two small check-dam-controlled catchments within the Huangfuchuan basin.

Study site

The Huangfuchuan catchment extends horizontally over 3,240 km^2 (Yu et al., 2006) and vertically between 824 and 1,474 m (Figure 1). The catchment belongs to the temperate semi-arid continental climate zone (Gao et al., 2005), with mean annual temperature and precipitation being approximately 7.5 °C and 400 mm respectively. Precipitation is seasonally uneven and mainly takes place in summer months (i.e. June-September) in the form of intensive and short-duration rainfall events (Tian et al., 2013). There are large areas of weathered bedrock (locally termed *Pisha* stone) where native vegetation has been destroyed by active hillslope and gully erosion (Yu et al., 2006). Soil types include chestnut soil, loessial soil, aeolian sandy soil, meadow soil and alluvial soil (Shi et al., 1999), most of which are prone to erosion (Yu et al., 2006). The catchment is characterized by severe soil erosion, contributing 0.5×10^8 t of sediment to the Yellow River each year (Yu et al., 2014). A large amount of conservation measures (e.g. check-dams, re-vegetation, the ‘Grain-for-Green’ project) have been applied in the catchment to control soil erosion and restore the environment since the 1970s (Zuo et al., 2016), largely altering the land cover.

Materials and Methodology

Model description

RUSLE

RUSLE, developed by Renard et al. (1991), is an empirical, spatially lumped model, which predicts soil loss from hillslopes driven by interrill (sheet) and rill erosion (Equation 1). However, RUSLE has often been used as a spatially distributed model in estimating soil erosion rates over large areas (Sun et al., 2014), through dividing the study area into small sub-units with uniform characteristics (i.e. grid cells), on which the model is implemented to calculate the soil loss.

$$A=R\ K\ L\ S\ C\ P \qquad （1）$$

where A is the estimated soil loss per unit area per unit time（t ha^{-1} yr^{-1}); R is the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), and represents the driving force of erosion; K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), reflecting the susceptibility of soil to erosion; LS is the slope length and slope gradient factors, reflecting the effect of slope length and slope gradient on erosion; *C* is the vegetation cover factor, accounting for the impact of vegetation coverage on soil erosion; and *P* is the erosion control practice factor, representing the benefit of a given conservation measure for soil loss.

PESERA

PESERA consists of three modules: hydrology, vegetation growth and erosion (Kirkby et al., 2008). The hydrological module is centered on a water balance, with precipitation divided into overland flow, evapotranspiration and soil water storage. TOPMODEL is employed to estimate monthly soil water storage, which is able to simulate runoff production in the infiltration-excess environments (e.g. Loess Plateau) (Beven and Kirkby, 1979). The vegetation growth model is based on a biomass carbon balance to update the vegetation cover, vegetation biomass and soil organic matter on a monthly basis. Total sediment yield is estimated as the transporting capacity of runoff flow, driven by erodibility, overland flow and local relief, weighted for fractional vegetation cover, assuming erodible materials are always ample for runoff wash (Kirkby et al., 2008, Li et al., 2016d). The sediment yield modelled by PESERA is interpreted as the erodible materials produced on hillslopes and delivered to the base of each hillslope. PESERA can be implemented in ‘point’ and ‘spatial’ modes. The point mode provides an estimate of soil erosion rates for an individual hillslope, while the spatial mode produces a spatially distributed estimate of soil erosion rates for hillslopes over a large area with the same algorithm being applied to each of the hillslopes.

Model implementation

In this study, RUSLE and PESERA were implemented at a spatial resolution of 30 m to assess the impact of 1990-2000 LUCC and 2000-2011 LUCC on soil erosion rates of the Huangfuchuan catchment. RUSLE and PESERA require climate data, topographic data, soil data and land use/cover data to operate. In order to examine the LUCC effect, climate, topography and soil input parameters of the models were set to constant values, and average values of 1990-2011 climate parameters were employed as climate inputs. The values of the corresponding input parameters for the two models were exactly the same to facilitate the comparison of their outputs.

Climate data (i.e. daily meteorological data) were provided by China Meteorological Administration National Meteorological Science Data Sharing Service Platform (http://data.cma.cn/site/index.html). The 30-m SRTM DEM was provided by the International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://datamirror.csdb.cn). Soil type data were derived from the 1:500,000 soil map of the Loess Plateau, which were provided by the Ecological Environment Database of Loess Plateau. Seven soil types were identified including dark loessial soil, castanozems, cultivated loessial soil, alluvial soil, aeolian soil, skeletol soil and litho soil. Most of the soils are easily erodible given their loose texture and low organic matter content (Yu et al., 2006). The land use/cover datasets (including vegetation cover expressed by the Normalized Difference Vegetation Index, NDVI) for 1990, 2000 and 2011 were derived from 30-m Landsat images downloaded from the Data Sharing Infrastructure of the United States Geological Survey (USGS) archive (http://glovis.usgs.gov/). The images were interpreted based on the unsupervised classification method (Mather and Tso, 2009), and seven land classification types were recognized including cropland, grassland, forest, residential land, sandy land (i.e. sand desert-like land), water body and scrubland (i.e. unmanaged garigue-like ecosystem with mixed shrubs, grass and bare land, with some trees). The land use/cover data were validated by Li (2016) based on field survey data and the accuracy was found to be over 85%. LUCCs were then examined through an overlay analysis of the resulting land classification maps for 1990, 2000 and 2011 in ArcGIS 10.2.

RUSLE

Rainfall erosivity factor (R)

A rainfall erosivity factor calculation method proposed by Zhang et al. (2002) was employed in this study (Equation 2). This method is based on daily rainfall data and has already been widely used over the Loess Plateau (Yu et al., 2006, Cheng et al., 2009). The *R* factor was firstly calculated based on the daily precipitation records from each of the nine precipitation stations within the catchment (Figure 1), and the average value was then derived using the Thiessen polygon weighting method.

$$R_{half\ \ month} = \alpha \sum_{k=1}^{m} (P_k)^{\beta} \tag{2}$$

where, k (k = 1,2, ..., m) is the number of erosive rainy days in a half month; P_k is the daily rainfall on the k_{th} day in half a month. P_k is equal to the actual rainfall if the actual rainfall is greater than the threshold value of 12 mm, which is the standard for erosive rainfall in China (Sun et al., 2014). Otherwise, P_k is equal to zero (Zhang et al., 2002).

$$\beta = 0.836\ \ 3 + (18.177/P_{d12}) + (24.455/P_{y12}) \tag{3}$$

$$\alpha = 21.586\beta^{-7.1891} \tag{4}$$

where, P_{d12} is the average daily rainfall that is over 12 mm and P_{y12} is the yearly average rainfall for days with rainfall over 12 mm.

Soil erodibility factor (K)

The *K* factor was calculated by the method (Equation 5) employed in the EPIC model (Wischmeier and Smith, 1978), which has been widely used in *K* factor estimation on the Loess Plateau due to its low data requirement (Cheng et al., 2009, Li and Zheng, 2012).

$$\mathrm{k} = \{0.2 + 0.3\ \ exp[-0.0256San(1 - Sil/100)]\}^{*}$$

$$(\frac{Sil}{Cla+Sil})^{0.3}(1 - -\frac{0.25C}{C+exp(3.72-2.95C)})^{*} \tag{5}$$

$$\left(1-\frac{0.75Sn}{\mathrm{Sn}+exp(-5.51+22.95Sn)}\right)$$

where *San*, *Sil* and *Cla* are the sand fraction (%), silt fraction (%), and clay fraction (%), respectively; *C* represents soil organic carbon content (%); and Sn is equal to 1-San/ 100.

Topographic factor (LS)

Traditional algorithms for *LS* calculation are usually limited to the region with slopes of ≤18% (Mccool et al., 1989). Liu et al. (1994) found that soil loss was linearly related to the sine of the slope angle based on soil loss data from natural runoff plots ranging from 9% to 55% slopes. Liu et al. (2000) found that slope length index did not change as slope steepness increased from 20% to 40% and 60%. In this study the formulas developed by McCool et al. (1989, 1997) were used to calculate the S factor for < 18% area (Equations 7 and 8) and L factor (Equation 6), and the formula developed by Liu et al. (1994) was employed to calculate the S factor for > 18% slopes (Equation 9).

$$L=\left(\frac{\gamma}{22.13}\right)^{m} \qquad \begin{cases} m=0.5 & \theta\geq 9\% \\ m=0.4 & 9\%>\theta\geq 3\% \\ m=0.3 & 3\%>\theta\geq 1\% \\ m=0.2 & 1\%>\theta\geq 0 \end{cases} \tag{6}$$

$$S=10.8\ \ sin\theta+0.03,\ \theta<9\%; \tag{7}$$

$$S=16.8\ \ sin\theta-0.5,\ 9\%\leq\theta\leq 18\%; \tag{8}$$

$$S=21.91\ \ sin\theta-0.96,\ \theta>18\% \tag{9}$$

where γ is the slope length (m); and m is a dimensionless constant depending on the percent slope (θ).

Vegetation cover factor (C)

The C factor was calculated using the method (Equation 10) which was developed by Cai et al. (2000), and has been applied over the Loess Plateau (Sun et al., 2014). In this method, the C factor is derived from vegetation coverage (f), which can be expressed by the NDVI (Equation 11). The NDVI was derived based on Landsat images of 1990, 2000 and 2011 using ENVI 5.1.

$$c = \begin{cases} 1 & f = 0 \\ 0.6508 - 0.3436lgf & 0 < f \leq 78.3\% \\ 0 & f > 78.3\% \end{cases} \tag{10}$$

$$f = \frac{(NDVI - NDVI_{soil})}{(NDVI_{max} - NDVI_{soil})} \tag{11}$$

Erosion control practice factor (P)

The values of the *P* factor for different land use/cover types were determined with reference to those provided by previous USLE modelling work undertaken by Yu et al. (2006) for the Huangfuchuan catchment.

PESERA

PESERA requires six climate inputs: monthly total precipitation, mean precipitation per precipitation day, coefficient of variation of precipitation per precipitation day, monthly temperature range, monthly temperature and monthly potential evapotranspiration (PET). Precipitation-related parameters were derived as monthly statistics of the daily records of the nine precipitation stations, which were then averaged using the Thiessen polygon weighting method. Temperature-related parameters were calculated as monthly statistics of daily records collected at the Hequ weather station (Figure 1) while PET was derived using the Penman Monteith Equation (Allen et al., 1998). The topographic input of PESERA, local relief, was calculated as the standard deviation of elevation based on the 30-m DEM. Soil parameters were derived from soil properties based on the pedotransfer functions given in the PESERA manual (Irvine and Kosmas, 2003). Land use/cover parameters were set in terms of the PESERA manual. PESERA usually operates with vegetation cover updated by its vegetation growth module, while RUSLE implements based on actual vegetation coverage. In this study, the code of the vegetation growth module in PESERA was modified to ensure it operated based on the actual vegetation coverage used for RUSLE derived from the landsat-image-based NDVI (Equation 11). In addition, the adjustable parameters of PESERA, which mainly impact runoff production, were set to values suggested for infiltration-excess dominated environments (i.e. Loess Plateau).

Model validation

RUSLE and PESERA predict soil erosion rates on hillslopes, and do not consider sediment production and transport in gullies and river channels. They should thus be validated by soil erosion measurements on hillslopes or river sediment yield that well reflects hillslope erosion intensity. In the

Huangfuchuan catchment, there are numerous check dams in the gully and river network (Li et al., 2016a, Tian et al., 2013), meaning that the connection between river sediment yield and hillslope erosion rates has been disturbed. These check dams and a lack of sediment yield sampling points for hillslope erosion (Tian et al., 2015) mean that formal model validation of spatial patterns of hillslope erosion across the whole catchment is not currently possible. However, sediment data from check dams enables local subcatchment validation which is useful. In the Huangfuchuan catchment, sediment yield from two small check-dam-controlled catchments, which are Huangjiagou (1.04 km^2) and Yangjiagou (0.69 km^2) (Figure 1), was available and determined by Li (2016) and Zhao et al. (2017) based on the sedimentation behind the dams. The specific sediment yield for Huangjiagou was found to be 155.1 t ha^{-1} yr^{-1} during 2001-2012 while that for Yangjiagou was 106.1 t ha^{-1} yr^{-1} during 2007-2011. These measurements were employed to assess the accuracy of RUSLE and PESERA predictions.

Results

LUCCs of the Huangfuchuan catchment

Grassland accounted for 70-80% of the area while other land use/cover types each accounted for less than 10% of the Huangfuchuan catchment (Table 1). Grassland was widely distributed over the catchment (Figure 2); cropland was mainly concentrated on the flat area along the river channels; residential areas were typically located along the main river channel; scrubland, forest and sandy land were dispersed across the catchment. During 1990-2011, grassland and residential land expanded, cropland, forest and water bodies shrunk, and sandy land and scrubland expanded during 1990-2000 and shrunk during 2000-2011 (Table 1). Average vegetation coverage of the catchment only slightly increased between 1990 and 2000 (38.3%-38.9%) as vegetation cover increase in areas classified as grassland, cropland, forest and scrubland was largely offset by vegetation cover decrease in other areas. Vegetation cover considerably increased during 2000-2011 (i.e. 38.9%-48.7%) as a result of increased vegetation coverage for all land classification types except residential areas.

Impacts of LUCCs on soil erosion rates modelled by RUSLE

According to the RUSLE predictions (Figure 3a), the spatial pattern of soil erosion rates in the Huangfuchuan catchment was similar in 1990, 2000 and 2011, for which average soil erosion rates were predicted to be 122.7 t ha^{-1} yr^{-1}, 130.5 t ha^{-1} yr^{-1} and 114.6 t ha^{-1} yr^{-1}, respectively. Areas with erosion rates over 80 t ha^{-1} yr^{-1} were widely distributed on the hillslopes of the catchment, while those with erosion rates less than 25 t ha^{-1} yr^{-1} were mainly concentrated in the flat floodplain and the northern part of the catchment (Figures 2 and 3a). Erosion rate shifts induced by the LUCC during 1990-2000 and 2000-2011 were mainly between -25 and 25 t ha^{-1} yr^{-1} (Figure 3b). Under the 1990-2000 LUCC, decreased soil erosion rate was mainly found in the northern part of the catchment and the floodplain, while increased soil erosion rates was found in other areas (Figure 3b). Under the 2000-2011 LUCC, most areas of the catchment experienced a decreased soil erosion rate, and areas with increased erosion rates were only scattered in the steep scrubland and sandy land (Figure 3b).

Mean soil erosion rates of different land classification types were generally in the sequence of scrubland > sandy land > cropland > grassland > forest (Table 2). For each of the five types, the standard deviation of soil erosion rates varied in the same way with average values of soil erosion rates. Under the 1990-2011 and 2000-2011 LUCC, mean erosion rates of grassland and cropland decreased, mean erosion rates of forest and scrubland increased first and then decreased, and that of sandy land decreased first and then increased.

Under the land-use/cover patterns of 1990, 2000 and 2011, most area of forest (52.2%-59.1%) was predicted to suffer from weak to moderate erosion (using the Ministry of Water Resources of China classification; Sun et al., 2014), while grassland (54.2%-58.8%), cropland (59.1%-68.8%), scrubland (82.2%-86.4%) and sandy land (68.3%-80.5%) were found to mainly suffer from intensive to severe erosion (Table 3a). Under the 1990-2000 and 2000-2011 LUCC, the area with weak to moderate erosion increased in grassland and sandy land, decreased in cropland and forest, and first increased and then decreased in scrubland. Areas with intensive to severe erosion increased in grassland, decreased in cropland, forest and sandy land, and first increased and then decreased in scrubland.

In terms of RUSLE, the direction (positive/negative) of mean predicted erosion changes induced by the land-use/cover transition was generally consistent with the sequence of mean erosion rates for different land classification types presented in Table 2. More specifically, most of the area was found to experience a negative erosion change when land use/cover changed from a less erosion-prone type (e.g. forest) to a greater erosion-prone type (e.g. sandy land) and vice versa (Table 2, Figure 4), eventually leading to overall erosion changes for the area in the same direction (Figure 5). However, this was not the case for the erosion change in the sandy land-scrubland transition, where the direction of predicted erosion change was opposite to the difference of mean erosion rates for sandy land and scrubland.

Impacts of LUCCs modelled by PESERA

PESERA predictions suggested that the spatial distribution of soil erosion rates in the catchment differed considerably (Figure 3c) between 1990, 2000 and 2011, for which average soil erosion rates were predicted to be 50.9 t ha^{-1} yr^{-1}, 51.3 t ha^{-1} yr^{-1} and 37.6 t ha^{-1} yr^{-1} respectively. Under the 1990-2000 and 2000-2011 LUCC, areas with erosion rates over 80 t ha^{-1} yr^{-1} were mostly distributed in steep sandy areas, while areas with erosion rates less than 25 t ha^{-1} yr^{-1} were concentrated in flat floodplain, central-eastern and central-western parts of the catchment (Figures 2 and Figure 3c). Under the 1990-2000 LUCC, soil erosion rates decreased in the eastern and southern areas and increased in the western areas, particularly in the northwestern parts of catchment (Figure 3d). Under the 2000-2011 LUCC, soil erosion rates decreased over the majority of the catchment, and increased only in some southern areas (Figure 3d).

Mean soil erosion rates for different land classification types were found to follow the order of sandy land > scrubland > grassland > cropland > forest. The standard deviation of soil erosion rates for each land-use type varied in the same way with its average soil erosion rates (Table 2). Under the 1990-2000 and 2000-2011 LUCC, mean soil erosion rates of grassland, sandy land and scrubland decreased, while that of cropland and forest increased first and then decreased.

Under the land use/cover patterns of 1990, 2000 and 2011, grassland (66.2%-78.8%), cropland (87.5%-95%) and forest (91.6%-97.4%) were found to mainly suffer from weak to moderate erosion (Table 3b), while most area of sandy land (74.7%-86.2%) was found to experience intensive to severe erosion. For the scrubland, areas with weak to moderate erosion and intensive to severe erosion were relatively balanced (47.5%-64.8% versus 35.2%-52.5%). Under the 1990-2000 and 2000-2011 LUCC, areas with weak to moderate erosion increased in grassland and sandy land, decreased in cropland and forest and increased first and then decreased in scrubland. Areas with intensive to severe erosion decreased in grassland and sandy land, increased first and then decreased in cropland and forest, and increased first and then decreased in scrubland.

Similar to RUSLE results, PESERA predicted erosion rates decreased over most of the area when converted to forest and increased for most of the area when converted to sandy land (Figure 4), leading to an overall erosion change of the corresponding land transition area following the above dominant changing direction (Figure 5). However, PESERA predicted erosion changes were complex for land use/cover transition among grassland, cropland and scrubland, and sometimes the changing directions altered between different periods. For example, in the cropland-grassland and cropland-scrubland area predicted erosion rates increased in over 68% of the area under the 1990-2000 LUCC and decreased in over 88% of the area under the 2000-2011 LUCC (Figure 4). In the scrubland-grassland area, predicted erosion rates increased in over 65% of the area under the 1990-2000 LUCC and decreased in over 61% of the area under the 2000-2011 LUCC.

Comparison of RUSLE and PESERA predictions

For the Yangjiagou and Huangjiagou catchment, mean erosion rates predicted by RUSLE (127.6 t ha^{-1} yr^{-1} – 159.6 t ha^{-1} yr^{-1}, 163.6 t ha^{-1} yr^{-1} – 170.8 t ha^{-1} yr^{-1}) were higher than the sediment yield measured behind the check-dams (106.1 t ha^{-1} yr^{-1}, 155.1 t ha^{-1} yr^{-1}), while PESERA predictions (51.8 ta ha^{-1} yr^{-1} – 60.0 t ha^{-1} yr^{-1}, 28.4 t ha^{-1} yr^{-1} – 72.7 t ha^{-1} yr^{-1}) were lower than the measured sediment yield (Table 4). The magnitude of difference between PESERA predictions and check-dam measurements was generally higher than that of difference between RUSLE predictions and measurements. For the Yangjiagou catchment the magnitude of the difference from the check dam value was closer between PESERA and RUSLE than at Huangjiagou and particularly for the 2011 land use/cover condition (Table 4).

Mean erosion rates modelled by RUSLE for different land use/cover types are generally higher than that modelled by PESERA. In 1990 R/P values (defined as the ratio between RUSLE and PESERA predictions presented in Table 2) for cropland and forest are 9.0 and 13.4 respectively, which are much higher than those in 2000 and 2011. In the scrubland, R/P was 4.3 for 1990, 6.0 for 2000 and 7.1 for 2011. R/P values for grassland and sandy land are generally no more than 2.4.

Under the 1990, 2000 and 2011 land use/cover pattern, areas of R>P accounted for 66.6%, 67.2% and 71.3% of the catchment area (Table 4), while areas with R<P occupied other area of the catchment. The former was widely spread within the catchment, while the latter was concentrated on the flat areas along the river networks and northwestern part of the catchment where the slope is relatively low (Figures 1 and 6). Areas with small differences (i.e. 15-50 t ha^{-1} yr^{-1}) between RUSLE and PESERA predictions are greatest among the five different levels shown in Table 5, while areas of ‘very high difference’ (> 200 t ha^{-1} yr^{-1}) are smallest. In the ‘no difference’ level, R>P accounts for less area than R<P. However, in ‘small difference’ to ‘very high difference’ levels, R>P accounts for more area than R<P, and ratios between areas of R>P and R<P increase from the ‘small difference’ level (1.9-3.0) to ‘very high difference’ (50.8-136.4).

Mean erosion rates predicted by RUSLE and PESERA increased with slope gradients. The former increased more rapidly with slope gradients (Figure 7a), while the latter decreased more rapidly with vegetation cover (Figure 7b). On < 5° slopes, mean RUSLE predictions are similar to mean PESERA predictions, while the former are considerably higher than the latter for > 5° slopes. Mean RUSLE predictions were always higher than mean PESERA predictions for different vegetation coverage values (Figure 7b) For a selected 1-km^2 area (Figure 1), the spatial pattern of RUSLE results corresponds well with that of slope gradient while the spatial pattern of PESERA results is well explained by that of vegetation cover (Figure 8 a-d). A point-based statistical analysis showed that the RUSLE predictions increased more rapidly with slope and PESERA predictions are better related to vegetation cover (Figure 8 e-f).

A linear relationship was not found between erosion rate changes predicted by RUSLE and PESERA for different land classification transition zones (Figure 4). Nevertheless, these two models did yield the same direction of erosion rate changes for certain areas. In the forest transition zone and sandy land transition zone, most of the area was predicted to experience an intensified erosion which eventually led to increased mean erosion rates (Figures 4 and 5). In the grassland, cropland and scrubland transition zones, erosion rates in most of the area were predicted to increase by RUSLE and PESERA when they were converted to sandy land and to decrease when they were converted to forest. Mean erosion rate changes for these areas, as predicted by RUSLE and PESERA, also changed in the same way (Figure 5). PESERA predictions became more uncertain than RUSLE predictions (i.e. PESERA predicted erosion changes were not so dominated by an individual changing direction) when each of the above three land use/cover types was converted to the other two (Figure 4), and mean predicted erosion rate changes for these areas often switched between slight increase and slight decrease (Figure 5). As a result, there were disagreements in the direction of change of mean erosion rates predicted by RUSLE and PESERA for these areas.

Discussion

Model comparison

To the authors’ knowledge, our study was the first to employ more than one model to assess soil erosion rates of the Loess Plateau and their reactions to LUCCs. Few of the contemporary Loess Plateau soil erosion models are suitable for regional-scale studies (Li et al., 2017c), while RUSLE and PESERA can be applied over large areas (e.g. the whole of the Loess Plateau). Our work is therefore meaningful for the selection and development of regional-scale soil erosion models for the Loess Plateau. RUSLE is an empirically statistical model, which was originally developed to estimate long-term average soil erosion rates for hillslopes. PESERA, as RUSLE, also assumes the study sites as a cascade of hillslopes (Li et al., 2016d), and its process-based nature allows it to simulate soil erosion related processes. RUSLE needs only six parameters to operate, while PESERA requires 128 input layers for process-based modelling (Kirkby et al., 2008). Overall, RUSLE is suitable for a quick assessment of soil erosion rates over large areas, while the PESERA model is theoretically capable of reproducing different components of soil erosion processes, and provides model users with detailed information on soil erosion processes. PESERA may also be theoretically more suitable than RUSLE for assessing the impacts of climate change, land-use shifts and land management practices, given it simulates a water balance (Bathurst, 2011).

We found that RUSLE results were generally closer than PESERA predictions to the check-dam-derived sediment yield, although the magnitude of difference from the Yangjiagou subcatchment was fairly close between the two models. Tian et al. (2015) also found that predicted average soil erosion rates for the Huangfuchuan catchment by RUSLE, were close to the average sediment yield measured for a different check-dam controlled small catchment, located in the vicinity of the Huangfuchuan catchment with similar environmental conditions. In addition, we also found that RUSLE results were higher than check-dam measurements while PESERA predictions were considerably lower than the measurements, possibly implying that RUSLE overestimated and PESERA underestimated soil erosion rates for the Huangfuchuan catchment. However, wider spatial validation across hillslopes was not undertaken since the hillslope erosion measurements were not available. In the future, effort should be made to enhance long-term hillslope soil erosion monitoring across selected different landscapes of the Huangfuchuan catchment and the Loess Plateau to accumulate data to support spatial model testing, comparison and development.

PESERA predictions are similar to RUSLE predictions on gentle slopes, but considerably lower than the latter on steeper slopes. The difference between RUSLE and PESERA predictions increases with slope gradient (Figures 7-8), demonstrating that RUSLE is more sensitive to topography than PESERA. This can be explained by the mechanisms of RUSLE and PESERA for steep-slope erosion modelling. RUSLE considers soil erosion characteristics on different slope gradients through incorporating the steep slope factor developed by Liu et al. (1994) and therefore responds well to slope increase. PESERA was originally developed to address soil erosion processes in Europe (Kirkby et al., 2008), where gentle-sloping topography is dominant. This means the algorithms of PESERA (particularly the soil erosion equation) were mainly established based on the data from gentle slopes and may result in underestimated erosion rates when applied to steep slopes. The above difference also demonstrates that PESERA may be suitable for erosion rate estimation on gentle areas rather than steep slopes of the Loess Plateau. However, steep slopes are the focus of the ‘Grain-for-Green’ program as soil erosion occurs frequently and vegetation has not recovered at these places (Xin et al., 2008).

We found that soil erosion rates predicted by PESERA were negatively related to the proportion of the ground covered by vegetation, while RUSLE modelled erosion rates did not correspond well with vegetation coverage (Figures 7-8). This means that PESERA is more sensitive to vegetation coverage than RUSLE (Karamesouti et al., 2016). The process-based nature of PESERA implies that the coupling of vegetation with hydrological processes (e.g. runoff production, evapotranspiration) in the model is more physically feasible than an empirical model such as RUSLE. Furthermore, given slopes and vegetation coverage are crucial factors for soil erosion, PESERA needs to better account for steep slope conditions while RUSLE needs to improve the incorporation of vegetation effects, enhancing their capacity of addressing key soil erosion-related research questions on the Loess Plateau.

Our results demonstrated that RUSLE erosion predictions for different land use/covers were considerably higher than PESERA predictions (Table 2). Similar results were also found for the RUSLE and PESERA comparison study conducted for Mediterranean areas (Karamesouti et al., 2016, Fernández and Vega, 2016). An overall R/P value (i.e. RUSLE predictions / PESERA predictions) of 2.7 is also consistent with the results of Karamesouti et al. (2016). The linear relationship was not found between RUSLE and PESERA predictions (Figure 4), demonstrating the spatial pattern of PESERA results and RUSLE results were not well correlated. This also confirms the finding of Karamesouti (2016) for the Mediterranean site. The difference may be partly attributed to the fact that RUSLE results depend more upon the topography while PESERA predictions are more related to vegetation coverage. Meanwhile, modelling mechanisms of RUSLE and PESERA may also be responsible for the difference. RUSLE predicts erosion rates directly based on the rainfall erosivity and does not explicitly consider runoff production processes (Renard et al., 1991), while PESERA explicitly simulates a water balance which is integrated with the growth of vegetation, and estimates soil erosion based on overland runoff (Kirkby et al., 2008). This means that the driving mechanism of erosion in these two models is actually different, although they were both developed to model rill and interrill erosion rates.

Impacts of LUCCs on soil erosion rates (implication for future soil conservation)

PESERA and RUSLE predicted that mean soil erosion rates for the Huangfuchan catchment increased under the 1990-2000 LUCC and decreased under the 2000-2011 LUCC. A modelling work conducted by Yu et al. (2014) also found that average soil erosion rates of the Huangfuchuan catchment have reduced while sediment yield of the catchment have also been found to reduce based on modelling work (Tian et al., 2015, Zuo et al., 2016) and catchment outlet sediment yield measurements (Zhao et al., 2013, Wang et al., 2011, Mu and Zhang, 2013) since the implementation of the ‘Grain-for-Green’ program. This is partly attributed to the fact that in 2000 the area of sandy land and scrubland, which are most erosion prone, was higher than in 1990 and 2011 (Table 1). However, since 1999 the ‘Grain-for-Green’ program has been implemented and vegetation coverage increased by 2011 and thus soil erosion was predicted to reduce. Meanwhile, climate change (i.e. precipitation reductions) and other conservation measures (e.g. check-dams, terraces) also play an important role in reducing runoff and sediment yield from the Huangfuchuan catchment (Zhao et al., 2013, Li et al., 2016a). This was not taken into account in our modelling work, and should thus be considered in future work.

Modelling results suggested that mean erosion rates of different land use/cover followed scrubland and sandy land > cropland and grassland > forest. Scrubland and sandy land had highest mean soil erosion rates and considerable areas were subject to intensive to severe levels of erosion for both models (Table 3). This demonstrates that scrubland and sandy land should be the focus of future soil and water conservation work in the Huangfuchuan catchment. Severe erosion on these land classification types can be reduced through vegetation restoration as soil erosion rates were found to decrease when land was converted to forest under the 2000-2011 LUCC (Figures 4 and 5). However, re-vegetation may not always be suitable for erosion control in the catchment as erosion rate changes, as predicted by PESERA, are subject to considerable uncertainties and increased erosion may occur when scrubland is converted to grassland (Figures 4 and 5). This may be because severe water scarcity resulting from low precipitation and high evapotranspiration largely limits the growth of natural vegetation and thus its erosion control function (Sun et al., 2013, Feng et al., 2016, Jiao et al., 2016). Therefore, soil erosion conservation on the Loess Plateau should be carried out by various measures (e.g. check-dams, terraces, re-vegetation) rather than by vegetation restoration only.

Our modelling results showed that mean soil erosion rates on < 25° slopes decreased while that on > 25° slopes increased under the 2000-2011 LUCC (Figure 7a), implying that the LUCC exacerbates erosion risk of steep hillslopes of the Huangfuchuan catchment. Soil moisture is one of the most important limiting factors for vegetation growth on the Chinese Loess Plateau (Gao et al., 2011, Feng et al., 2016). Jia et al. (2005) found that soil moisture content decreased with increased slope gradients in the catchment, meaning that > 25° is more likely to subject to soil moisture deficit than < 25°. Such a situation may be exacerbated by recently warmer and drier climate in the catchment (Zuo et al., 2016), eventually limiting the growth of vegetation on > 25° slopes and resulting in increased soil erosion. Mass movements (e.g. landslides) occur frequently on steep hillslopes of the Loess Plateau particularly when vegetation cover is limited (Wang et al., 2005, Yu et al., 2009, Yu and Li, 2012, Yang et al., 2017). Therefore, further work is urgently needed to improve our understanding of the processes and underlying mechanisms of soil erosion on steep slopes, and to conserve soil on these areas.

Overall, our findings improved the understanding on the effect of LUCC on soil erosion and also the practical applicability of models in predicting soil erosion rates. The predicted spatial pattern of soil erosion change for the Huangfuchuan catchment was quantitatively assessed. This provides land managers with a spatially-distributed indicator of potential erosion risk or erosion mitigation potential through land management decisions. Our results also have implications for soil erosion conservation and eco-environment restoration on other areas of the Chinese Loess Plateau. Using our modelling results, land managers will be able to develop spatially-targeted erosion conservation and protection strategies, enabling limited funds and resources to be preferentially allocated to locations where management interventions might have the greatest impact.

Conclusions

In our study, two extensively applied models (RUSLE and PESERA) were employed to investigate the impact of LUCCs between 1990 and 2011 on soil erosion rates for the Huangfuchuan catchment, and their modelling results were compared. The Huangfuchuan catchment is dominated by grassland (over 70%), and vegetation coverage increased considerably since the implementation of the ‘Grain-for-Green’ program in 1999. Modelling results suggested that mean soil erosion rates of the Huangfuchuan catchment increased under the 1990-2000 LUCC and decreased under the 2000-2011 LUCC. Sandy land and scrubland should be the focus of future soil and water conservation work given that soil erosion rates of different land cover types modelled by RUSLE and PESERA usually follow the sequence of sandy land and scrubland > cropland and grassland > forest. Modelling results also found that areas with slopes over 25° increased under the 2000-2011 LUCC possibly because of limited vegetation growth resulting from severe soil moisture deficit. Future research should focus on soil erosion processes and their conservation on steep slopes. A comparison of modelling results with sediment yield derived from two small check-dam controlled subcatchments demonstrated that RUSLE predictions were closer to field measurements than PESERA results, although for one subcatchment the magnitude of the difference from the check dam value was close between the two models. Model comparisons showed that RUSLE predicted higher erosion rates than PESERA for most area of the catchment, yielding considerably higher predicted mean erosion rates for different land uses/covers, particularly for those with steep slopes. RUSLE and PESERA predictions were not linearly correlated, possibly attributable to the difference in their underlying principles and their sensitivity to crucial parameters. The PESERA model will need further improvement to better account for soil erosion processes on steep slopes of the Loess Plateau, while RUSLE will need improvements to better incorporate vegetation effects.

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Table 1 Area of different land-cover types and their vegetation coverage in the Huangfuchuan catchment for 1990, 2000 and 2011

Land use	1990				2000				2011			
	Area		Vegetation coverage		Area		Vegetation coverage		Area		Vegetation coverage	
	km^2	%	Mean (%)	Std.	km^2	%	Mean (%)	Std	km^2	%	Mean (%)	Std
Grassland	2347.1	72.3%	38.6	15.5	2449.3	75.5%	39.1	13.2	2579.4	79.5%	49.7	13.7
Cropland	321.4	9.9%	50.5	13.8	197.0	6.1%	52.8	11.8	157.5	4.9%	54.9	10.9
Residential	5.7	0.2%	46.6	18.5	8.9	0.3%	43.9	21.3	29.0	0.9%	32.1	22.5
Forest	71.3	2.2%	50.2	14.9	32.4	1.0%	53.2	14.0	26.2	0.8%	67.6	13.0
Sandy land	145.8	4.5%	19.8	12.1	148.1	4.6%	17.6	12.3	130.2	4.0%	32.3	12.9
Water	85.7	2.6%	26.6	21.1	22.6	0.7%	25.3	19.9	49.1	1.5%	28.6	19.7
Scrubland	268.3	8.3%	31.2	16.4	387.2	11.9%	38.1	14.4	274.0	8.4%	48.0	15.5

Table 2 Soil erosion rates and R/P (RUSLE predictions/PESERA predictions）modelled by RUSLE and PESERA for different land-cover types in the Huangfuchuan catchment with the 1990, 2000 and 2011 land cover.

Period	Land cover	Soil erosion (RUSLE)/(t $ha^{-1}yr^{-1}$)		Soil erosion (PESERA)/(t $ha^{-1}yr^{-1}$)		R/P
		Mean	Std	Mean	Std	
1990	Grassland	91.6	95.9	50.1	57.2	1.8
	Cropland	146.5	188.0	16.2	29	9.0
	Forest	61.6	65.9	4.6	20.1	13.4
	Sandy land	278.6	290.7	143.5	99.3	1.9
	Scrubland	335.1	353.8	78.5	77.2	4.3
2000	Grassland	86.1	91.1	47.2	52.9	1.8
	Cropland	135.9	194.6	28.8	22.3	4.7
	Forest	84.1	79.5	22	23.7	3.8
	Sandy land	206.9	253.7	128	92.3	1.6
	Scrubland	392.3	368.1	65.7	65.4	6.0
2011	Grassland	83.3	88.5	34.1	40.9	2.4
	Cropland	109.8	160.2	27	20.9	4.1
	Forest	52.8	62.3	11.8	24.6	4.5
	Sandy land	234.8	269.5	111.8	87.3	2.1
	Scrubland	390.3	380.8	54.9	65.3	7.1

Table 3 Area of different erosion levels, derived based on the modelling results of RUSLE (a) and PESERA (b), for different land-cover types of the Huangfuchuan catchment with the 1990, 2000 and 2011 land cover.

Erosion class	Grassland			Cropland			Forest			Sandy land			Scrubland		
	1990	2000	2011	1990	2000	2011	1990	2000	2011	1990	2000	2011	1990	2000	2011
a. RUSLE model															
Weak erosion	17.0%	17.6%	17.6%	30.7%	37.1%	39.9%	18.0%	19.1%	30.9%	18.8%	31.0%	23.7%	16.9%	12.9%	13.9%
Slight erosion	0.5%	0.5%	1.4%	0.0%	0.0%	0.1%	13.6%	17.0%	9.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Moderate erosion	23.7%	25.8%	26.8%	0.6%	0.7%	0.9%	22.6%	16.1%	19.0%	0.7%	0.7%	0.9%	0.8%	0.8%	0.9%
Intensive erosion	16.3%	16.1%	15.9%	17.9%	17.4%	19.3%	17.8%	19.2%	15.5%	0.6%	0.8%	0.9%	0.9%	0.8%	0.8%
Very intensive erosion	23.2%	22.6%	22.0%	16.7%	13.9%	14.9%	18.6%	22.3%	18.0%	19.3%	20.0%	20.9%	16.0%	12.1%	13.9%
Severe erosion	19.3%	17.5%	16.3%	34.0%	30.9%	24.9%	9.3%	6.4%	7.3%	60.6%	47.5%	53.6%	65.3%	73.5%	70.5%
Total Area (km^2)	2333.0	2438.9	2568.9	324.2	200.7	160.8	75.1	34.0	27.1	148.2	150.6	132.4	273.9	389.7	278.1
b. PESERA model															
Weak erosion	19.6%	17.8%	28.2%	54.7%	13.0%	14.0%	92.2%	31.6%	68.2%	0.7%	0.8%	1.3%	11.4%	8.9%	17.7%
Slight erosion	26.0%	27.9%	30.9%	32.6%	40.6%	43.7%	2.9%	41.5%	27.1%	3.0%	4.4%	7.2%	17.8%	23.0%	27.7%
Moderate erosion	20.6%	23.1%	19.7%	7.7%	33.9%	32.1%	2.3%	18.5%	1.7%	10.1%	12.8%	16.8%	18.2%	23.2%	19.4%
Intensive erosion	13.7%	13.5%	10.7%	2.2%	9.7%	7.8%	1.3%	5.4%	1.1%	15.4%	17.7%	19.4%	15.6%	16.1%	12.9%
Very intensive erosion	13.7%	12.4%	8.1%	1.8%	2.5%	2.1%	0.9%	2.6%	1.2%	32.6%	32.6%	30.5%	21.6%	18.5%	13.8%
Severe erosion	6.4%	5.3%	2.5%	1.0%	0.3%	0.3%	0.4%	0.4%	0.8%	38.2%	31.6%	24.8%	15.3%	10.3%	8.5%
Total Area (km^2)	2333.0	2438.9	2568.9	324.2	200.7	160.8	75.1	34.0	27.1	148.2	150.6	132.4	273.9	389.7	278.1

Notes: Erosion levels were defined in terms of the technological standard of soil and water conservation, SL190-2007, issued by the Ministry of Water Resources of China (Sun et al., 2014). Weak erosion, slight erosion, moderate erosion, intensive erosion, very intensive erosion and severe erosion refer to soil erosion rates of below 10 t ha^{-1} yr^{-1}, 10-25 t ha^{-1} yr^{-1}, 25-50 t ha^{-1} yr^{-1}, 50-80 t ha^{-1} yr^{-1}, 80-150 t ha^{-1} yr^{-1}, and over 150 t ha^{-1} yr^{-1} respectively.

Table 4 Comparison of measured and modelled erosion rates for two small check-dam-controlled catchments, Yangjiagou and Huangjiagou

Catchment	Measured sediment yield (t ha^{-1} yr^{-1})	Modelled erosion rates (t ha^{-1} yr^{-1})			Measurement/prediction difference[a]	
		RUSLE	PESERA	Land use/cover	RUSLE	PESERA
Yangjiagou	106.1	127.6	51.8	1990	21.5	-54.3
		159.6	23.7	2000	53.5	-82.4
		153.6	60	2011	47.5	-46.1
Huangjiagou	155.1	163.6	72.7	1990	8.5	-82.4
		167.3	28.4	2000	12.2	-126.7
		170.8	54	2011	15.7	-101.1

a, the difference between measured specific sediment yield and modelled erosion rates was calculated as modelling results of RUSLE and PESERA minus corresponding measurements.

Table 5 Area of the difference between RUSLE and PESERA predictions under the 1990, 2000 and 2011 land use/cover

∆Erosion (RUSLE-PESERA) of the area (%)		1990		2000		2011	
		Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
No difference [<15 t ha^{-1}yr^{-1}]	R>P	214.0	6.6%	233.5	7.3%	219.6	6.8%
	R<P	552.9	17.2%	484.1	15.0%	574.7	17.8%
Small difference [15-50 t ha^{-1}yr^{-1}]	R>P	610.2	18.9%	657.6	20.4%	772.6	24.0%
	R<P	326.5	10.1%	367.6	11.4%	262.3	8.1%
Moderate difference [50-100 t ha^{-1}yr^{-1}]	R>P	528.3	16.4%	479.4	14.9%	547.4	17.0%
	R<P	140.8	4.4%	147.7	4.6%	67.8	2.1%
High difference [100-200 t ha^{-1}yr^{-1}]	R>P	445.6	13.8%	403.6	12.5%	428.9	13.3%
	R<P	50.1	1.6%	51.9	1.6%	17.7	0.5%
Very high difference [>200 t ha^{-1}yr^{-1}]	R>P	345.5	10.7%	388.8	12.1%	327.4	10.2%
	R<P	6.8	0.2%	6.5	0.2%	2.4	0.1%

Figure captions

Figure 1 Basic information for the Huangfuchuan catchment including location, slope, hydro-meteorological stations, and river networks, location of Huangjiagou and Yangjiagou check-dam controlled catchment and 1 km2 area selected for the further analysis in Figure 7.

Figure 2 Land use/cover pattern of the Huangfuchuan catchment in 1990, 2000 and 2011.

Figure 3 Soil erosion rates modelled by RUSLE (a) and PESERA (c) and erosion rate changes under the 1990-2000 and 2000-2011 LUCC derived based on the modelling results of RUSLE (b) and PESERA (d).

Figure 4 Relationship between erosion rate changes (1990-2000 and 2000-2011) modelled by PESERA and those modelled by RUSLE. The percentages refer to the number of points in relevant quadrants while those close to the axes stand for the number of points with a value of zero (i.e. no erosion changes were predicted by RUSLE and/or PESERA).

Figure 5 Mean and standard deviation of soil erosion rates predicted by RUSLE and PESERA for land cover transition zones in the Huangfuchuan catchment during 1990-2011.

Figure 6 The difference between RUSLE and PESERA predicted erosion rates (RUSLE predictions minus PESERA predictions) under the 1990, 2000 and 2011 land use/cover pattern.

Figure 7 Mean value and standard deviation of soil erosion rates predicted by RUSLE and PESERA for areas with different slopes (a) and vegetation cover (b) in the Huangfuchuan catchment under the 1990, 2000 and 2011 land cover.

Figure 8 RUSLE/PESERA-predicted erosion rates (a, b) and their relationships with slope gradient/vegetation cover (c, d) for a 1-km2 area (e, f), of which the location is shown in Figure 1, under the 2000 land cover.