Science of the Total Environment 635 (2018) 673–686

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Current and future assessments of soil erosion by water on the Tibetan Plateau based on RUSLE and CMIP5 climate models

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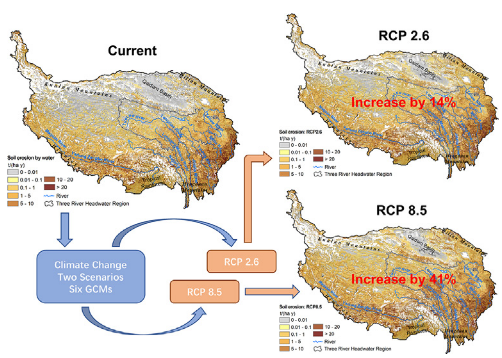
HIGHLIGHTS

- Present soil erosion by water on the Tibetan Plateau was predicted.
- The impact of the climate change was evaluated and incorporated into the prediction of *R* factor in 2050.
- Erosion rate in 2050 was estimated with the corresponding projected *R* factor and other erosion factors.
- Estimated erosion rates in 2050 could potentially increase by 14% to 41% from current rates.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 December 2017
Received in revised form 9 April 2018
Accepted 10 April 2018
Available online xxxx

Editor: Ouyang Wei

Keywords:
Soil erosion by water
Future erosion
Tibetan Plateau
Climate change
RUSLE

ABSTRACT

Soil erosion by water is accelerated by a warming climate and negatively impacts water security and ecological conservation. The Tibetan Plateau (TP) has experienced warming at a rate approximately twice that observed globally, and heavy precipitation events lead to an increased risk of erosion. In this study, we assessed current erosion on the TP and predicted potential soil erosion by water in 2050. The study was conducted in three steps. During the first step, we used the Revised Universal Soil Equation (RUSLE), publicly available data, and the most recent earth observations to derive estimates of annual erosion from 2002 to 2016 on the TP at 1-km resolution. During the second step, we used a multiple linear regression (MLR) model and a set of climatic covariates to predict rainfall erosivity on the TP in 2050. The MLR was used to establish the relationship between current rainfall erosivity data and a set of current climatic and other covariates. The coefficients of the MLR were generalised with climate covariates for 2050 derived from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) models to estimate rainfall erosivity in 2050. During the third step, soil erosion by water in 2050 was predicted using rainfall erosivity in 2050 and other erosion factors. The results show that the mean annual soil erosion rate on the TP under current conditions is 2.76 t ha^{-1} y^{-1}, which is equivalent to an annual soil loss of 559.59 × 10^6 t. Our 2050 projections suggested that erosion on the TP will increase to 3.17 t ha^{-1} y^{-1} and 3.91 t ha^{-1} y^{-1} under conditions represented by RCP2.6 and RCP8.5, respectively. The current assessment

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https://doi.org/10.1016/j.scitotenv.2018.04.146

and future prediction of soil erosion by water on the TP should be valuable for environment protection and soil conservation in this unique region and elsewhere.

1. Introduction

Soil erosion by water has become one of the greatest global threats to the environment (Chappell et al., 2016; Navarro-Hevia et al., 2016). As a result of soil erosion by water, soil condition, water quality, species habitats and the provision of ecosystem services are negatively affected (Amundson et al., 2015; Teng et al., 2016). It is important to quantify the impacts of soil erosion by water and to develop effective measures for soil and water conservation. Soil erosion models are often employed to assess the risk of soil loss (Karydas et al., 2014). Among them, the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997) has been applied commonly to estimate long-term soil erosion rates from hillslopes in large-scale studies (Panagos et al., 2015; Teng et al., 2016).

The effects of climate change on soil erosion by water have been described by researchers (Garcia-Fayos and Bochet, 2009; Li and Fang, 2016; Yang et al., 2003). The characteristics of rainfall (rainfall amount, intensity and spatio-temporal distribution) directly affect soil erosion. In addition, rising temperature also indirectly affects soil erosion (Li and Fang, 2016). According to the Fifth Assessment Report (AR5) of the IPCC (Intergovernmental Panel on Climate Change), global mean precipitation and surface temperature have changed significantly, and the report suggests that these changes are very likely to continue during the 21st century (IPCC, 2014). The effects are still uncertain; therefore, the magnitude of the effects of climate variability on soil erosion needs to be investigated.

The Tibetan Plateau (TP), which is often known as “the Third Pole” of the Earth (Qiu, 2008), has an average elevation of >4000 m above sea level. The TP, which is also known as the “Asian Water Tower” (Immerzeel et al., 2010), is the source of the region's major river systems and provides water to >1.4 billion people (over 20% of the global population). Soil erosion by water in the TP will not only impact drinking water quality for both people and livestock in downstream rivers but also affect food security in Southeast Asia. Thus, the TP is of immense importance to both the climate and the ecosystems of Asia and the world, and more attention should be paid to the erosion status of these regions (Du et al., 2004; Li et al., 2015).

The TP is affected by regional and global climate change through thermal and mechanical forcing mechanisms (Su et al., 2013), and appears to be particularly sensitive to variations in climate and has become one of the most degraded ecosystems in the world (Baumann et al., 2009). During the 21st century, a warming trend of 0.47 °C $(10\,\mathrm{yr})^{-1}$ to 0.73 °C $(10\,\mathrm{yr})^{-1}$ over the TP under the representative concentration pathway 8.5 (RCP8.5) scenario is predicted by the global climate models from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Su et al., 2013). Research of soil erosion by water on the TP may provide one of the last remaining chances to study the impact of climate change on water erosion over a large region because many of the natural ecological processes and feedbacks are still intact in this area (Chen et al., 2013). However, erosion prediction and risk assessment for the TP is a great challenge, particularly if associated with climate change.

Soil erosion by water on the TP has been estimated by several scientists, but these have been mostly focused on a catchment (Chaplot et al., 2005; Hren et al., 2007; Jiang and Zhang, 2016) or local scale (Pan et al., 2010; Wang et al., 2014; Xu et al., 2009). Due to the high altitude, harsh weather conditions, and remoteness of the plateau, the quantitative and direct measurements of water erosion over the TP are difficult, expensive, time-consuming and nearly impossible. There is limited knowledge regarding quantitative erosion rates over the whole TP. The lack of field measurements has created a need to develop new methods to predict soil erosion by water and the impacts of future climate change on erosion in this area. Modelling current and future erosion rates is crucial in an assessment of potential future environmental problems and land degradation on the TP (Wang et al., 2014).

Thus, the aims of this study are as follows: first, to predict the current soil erosion by water on the TP using RUSLE; second, to predict the rainfall erosivity factor value in 2050 with climate projections from six CMIP5 Global climate models (GCMs); and third, to estimate soil erosion by water in 2050 with the corresponding projected rainfall erosivity. Our assumption is that soil erosion by water on the TP is driven largely by climate.

2. Materials and methods

In this study, the current soil erosion by water was estimated using RUSLE, where the factors were derived from various points and remote-sensing data sets. The current rainfall erosivity value was modelled using a multiple linear regression (MLR) under current climate conditions. We generalised this model but used the future climate data from six GCMs to predict the rainfall erosivity value in 2050. The potential soil loss in 2050 was then predicted by rainfall erosivity and other erosion factors. We describe our approaches as follows:

2.1. RUSLE model

RUSLE is a linear equation used to quantify soil erosion by water from hillslopes (Kinnell, 2010). RUSLE is suitable for predicting long-term soil erosion rates over large areas according to the following equation:

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

where A is the average rate of soil erosion by water at each cell (t ha^{-1} y^{-1}); R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} y^{-1}); K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}); LS is the slope length and steepness factor; C is the cover management factor; and P is the support practice factor. We describe the derivation of the factors below.

The R factor is an indicator of the potential of precipitation to detach and transport soil particles. In this study, daily observed precipitation data provided by the National Climate Centre of the China Meteorological Administration (CMA) and the Tropical Rainfall Measuring Mission (TRMM) were used in our calculation of R. For the 15-year period from 2002 to 2016, 105 rain gauge stations were available across the TP (Fig. 1). We used rainfall estimates from TRMM 3B42 Version 7, which have a spatial resolution of 0.25° × 0.25° and a temporal resolution of 3 h (Ma et al., 2017; Teng et al., 2014). The R factor was calculated following the approach presented in Teng et al. (2017). Collocated cokriging (ColCOK) was used to merge the daily rainfall data from the rain gauge stations and TRMM measurements to improve the quality of the precipitation data. The merged daily rainfall data was then used to calculate R with a power function model, which has been widely used in China and implemented by the National Water Conservancy Survey (Duan et al., 2016; Teng et al., 2017).

$$R_i = m \sum_{j=1}^{k} \left(d_j^i\right)^n \tag{2}$$