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Water erosion response to rainfall and land use in different drought-level years in a loess hilly area of China

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ABSTRACT

Due to rainfall variation and poor land cover, water erosion in the loess hilly area is severe and experiences high temporal fluctuations, which increase the difficulties of erosion quantification, prediction and control. In this study, 15 runoff plots were implemented in Dingxi, a typical loess hilly area of Gansu Province since 1986. Three typical years representing WY (wet year), NY (normal year) and DY (drought year) were firstly filtered based on the consecutive rainfall-erosion data and an aridity index. Then, water erosion dynamics involving five land uses (cropland, alfalfa, scrubland, woodland and grassland) in the three typical years were analyzed. The following results were found. Firstly, the most severe annual erosion rates did not appear in WY, but in DY. Moreover, the rates in DY were far higher than those in NY and WY. Secondly, although total rain depth and number of events were in the order of WY > NY > DY, mean maximal intensity of erosive rainfall however, was in the order of DY > NY > WY. This finding is important for erosion control. Namely, we cannot judge water erosion degree just from annual rainfall. More attention should be paid to the specific rainfall variables and distributions. Thirdly, different land uses played an important role with sea buckthorn reducing water erosion in contrast to spring wheat cultivated on steep slopes. Lastly, regardless of different drought-level years, only a few number of events with high intensities were responsible for the majority of annual soil and water loss.

1. Introduction

Soil erosion caused by water is one of the most severe erosion forms across the globe and has attracted high attention during the past, mainly due to its on-site and off-site destructive effects (Fu, 1989; Römkens et al., 2001; de Lima et al., 2003; Davision et al., 2005; Chen et al., 2007a; Casalí et al., 2008; Wei et al., 2009). Abundant studies have uncovered that persistent severe erosion can deteriorate soil conditions, reduce water holding capacity, decrease aggregate stability and soil biodiversity, and bring serious ecological crisis such as eutrophication, non-point pollution and eventually land degradation (Bosch and Hewlett, 1982; Gafur et al., 2003; Singer and Shainberg, 2004; Ulén and Kalisky, 2005; Jin et al., 2008). For example, a study in America indicated that the crop yields would be reduced by 2 to 4% if current water erosion rates continue for the next 10 decades (Trimble and Crosson, 2000). New reports claim that there is a clear relation between erosion and changes in carbon cycle and precipitation (Weltzin et al., 2003; Nearing et al., 2005). Measurements at the field scale indicate that the soil organic carbon pool (SOCP) decreases significantly after long-term severe erosion, which in turn may release huge amounts of CO_2 to the atmosphere and eventually contribute to global warming (Lal and Pimentel, 2008). Controlling severe erosion thus becomes more urgent to ensure the sustainability of our terrestrial systems facing the 21st century.

Natural processes of soil and water loss fluctuate highly between different seasons and years, and this is more significant in the fragile arid environments with sparse vegetation covers (Merz et al., 2006). These fluctuations increase the difficulties of accurate erosion measurement and prediction (Hogarth et al., 2004; Busnelli et al., 2006). Moreover, such intra- and inter-annual changes in water erosion are complex and caused by many synergistic reasons (Busnelli et al., 2006; Chen et al., 2007b). Among these factors however, the spatiotemporal variations of rainfall play a key role (Apaydin et al., 2006; Wei et al., 2007, 2009; Baigorria et al., 2007). Due to poor vegetative cover and fragile ecosystem, surface hydrological responses are even sensitive to small fluctuations of rainfall in the semiarid regions (Yair and Raz-Yassif, 2004; Wang et al., 2005; Nearing et al., 2005; Leblance et al., 2008). Knowledge about the role of rainfall temporal variations on water erosion is thus significant for erosion control and larger-scale hydrological predictions.

Besides rainfall, land use also influences water erosion (Braud et al., 2001; Dunjó et al., 2004; Foley et al., 2008). Deforestation, cultivation of steep slopes and other strong agricultural activities have induced severe erosion and land degradation in huge areas around the

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world (Bosch and Hewlett, 1982; Gafur et al., 2003; Chen et al., 2007a). Proper land use adjustment and vegetation restoration, however, can improve the effectiveness of land cover, consolidate the heath and stability of local ecosystems, and reduce the sensitivity of soil erosion and water loss to temporal changes in rainfall (Dunjó et al., 2004; Merz et al., 2006; Eugenia et al., 2007).

More notably, water erosion in the key loess hilly region of China shows a complex pattern of seasonal variability, with wide and unpredictable rainfall fluctuations from year to year (Chen et al., 2007b). There is a common sense that heavier rainfall or more annual rain causes more severe soil erosion and water loss (local questionnaire, unpublished materials). Videlicet, there is a positive relation between water erosion and rainfall depth. However, is this cognition always consistent with reality? Does the most severe water erosion always appear in the wettest year, and vice versa? Can wise land use reduce or even eliminate the temporal fluctuation of water erosion? These questions will be treated in this study.

Based on field measurement data, three typical years which represent a WY (wet year), NY (normal year) and DY (drought year) will be identified. Then, the characteristics of rainfall and corresponding water erosion responses under five land use types will be analyzed regarding: (1) water erosion dynamics in different drought-level years, (2) water erosion in relation to land use, (3) interaction between rainfall and land use regarding water erosion in different drought-level years.

2. Study area

The study was conducted in a typical hilly loess area named Anjiapo catchment (35°33′–35°35′N, 104°38′–104°38′E) in Dingxi, Gansu, in the western part of the Chinese Loess Plateau. According to the water deficit index (WDI) and the aridity index (AI), this area is semiarid and dominated by warm-humid summers and cold-dry winters (Huang et al., 2005; Chen et al., 2007a, 2007b). Mean annual precipitation (from 1956 to 2006) in this region is 427 mm/yr, of which the majority (more than 80%) falls from May to September (Wei et al., 2007). The historical record of maximum annual precipitation was 722 mm in 1967, and minimum record was 246 mm in 1982. The mean annual pan evaporation can reach 1510 mm/yr.

The soils developed from loess, which ranges in depth from 40 to 60 m. Groundwater is not available for vegetation growth due to the deep loess. Rainfall is thus the only water resource. Deep percolation can be neglected in most cases owing to limited rainfall. Dominant soil in the region is a calcic Cambisol (FAO-UNESCO, 1974) with a clay content of 33–42%, organic matter of 4–13 g/kg, and a bulk density from 1.09 to 1.36 g cm^{-3} within 2 m depth (Huang et al., 2004). Most of the natural vegetation has been converted to rain-fed farmland, causing a loss of ground cover protection. The majority of the remainders between the fields are secondary shrubs, grasses and some other artificial vegetation.

3. Methodology

3.1. Materials and field treatments

Fifteen runoff-erosion plots were collocated on a hillslope near the meteorological field station of the Dingxi Soil and Water Conservation Institute. They constitute five land use types with three replications (10°, 15°, 20°) at a mean slope of 26.80% in the experimental plots. (1) Cropland (Spring wheat: *Triticum aestivum* L. cv Leguan. Size: 10 m × 5 m): Field management was similar to that used by local farmers: the wheat was sown in April and harvested manually in late July or early August. (2) Alfalfa (*Medicago sativa* L. Size: 10 m × 5 m): Seeds were drilled or broadcasted in April and harvested in late July. (3) Scrubland (Sea buckthorn: *Hippophea rhamnoides* L. Size: 10 m × 10 m): Saplings of sea buckthorn were planted in 1.0 m by 1.0 m spacing in March, 1986. Litter remained on the plots during the experiment. Few human disturbances existed due to the plant's high density and spiny branches. (4) Woodland (Chinese pine: *Pinus tabulaeformis* Carr. Size: 10 m × 10 m): Chinese pine saplings were planted in 3.0 m rows and 1.5 m columns in March, 1986, without artificial pruning and irrigation. (5) Semi-natural grassland (Size: 10 m × 5 m): This plot was left growing without any human disturbance since 1986 when cropland was abandoned, and wheatgrass (*Agropyron cristatum* L. Gaertn.) has now become the dominant species in the patch. It is a typical grass species in cold-dry regions. The mean annual vegetative coverage of the five land use types from 1986 to 2006 was 51% (cropland), 54% (alfalfa), 93% (scrubland), 66% (woodland) and 89% (semi-natural grassland), respectively.

3.2. Measurements

Daily rainfall events were recorded by two automatic pluviometers within the study area and stored by a data logger. Several key rainfall variables including amount, duration and maximum intensity in 30 min were calculated. The corresponding event runoff volume from each plot in each rainfall event was recorded simultaneously. Sediment from the fifteen plots was firstly sampled using 250 ml bottles, then allowed to settle and separated from the water, dried in an air forced oven to constant weight at 105 °C. The data were then used to calculate the related hydrological indices representing the degrees of soil and water loss. Totally, data from 1986 to 2006 (data in 2000 and 2001 missing) were collected for further analyses.

3.3. Aridity classification

Climatologist use an "aridity index" (e.g. the ratio of potential evaporation to rainfall) to help classify desert (arid) or humid areas, studying drought and related hydrological processes (Western et al., 2004; Cook et al., 2007). In the study area, rainfall input was considered as the only water source and evaporation as basic water output leading to an index for different drought-level year classification.

$$AI = EV / RD \tag{1}$$

where AI, EV and RD denote aridity index, pan evaporation and rainfall depth, respectively.

3.4. Statistical methodology

Two indicators were selected to quantify surface runoff and soil erosion.

(1) Water loss ratio

$$RR = (SR / RD) \times {}^{100}/_{100} \tag{2}$$

where RR, SR and RD refer to runoff ratio, surface runoff and rainfall depth, respectively.

(2) Erosion rate

$$ER = SL / PA \tag{3}$$

where ER, SL and PA indicate erosion rate, soil loss and area of each experimental plot, respectively.

All the data were analyzed with the software of SPSS13.0 for windows.