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Effects of crop rotation and rainfall on water erosion on a gentle slope in the hilly loess area, China

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ABSTRACT

Cultivation on steep land has long been blamed as a major contributor of water erosion in many fragile regions of the world. Soil and water loss from gentle slopes, however, are always subjectively considered less important and are even neglected in practice. In this study, 21 plots including seven crop-rotation types (CRTs) under three different slight gradients (10°, 15°, 20°), were established in Dingxi, a typical semiarid hilly loess area in China. Eight consecutive years of erosion data under different gentle-slope cultivation conditions were compared and analyzed. The most interesting and key finding is that water erosion remained far higher on slopes with gradients of less than 20° than the tolerable criterion, even when some CRT measures and field treatments (e.g., contour cultivation, stiletto, minimum tillage, and crop-shrub intercropping) were implemented. Newfield techniques targeting erosion control on gentle slopes should be developed. Secondly, compared with other crop species, potato cultivation under sloping conditions was confirmed to cause the highest soil and water loss and should be strictly forbidden at large scales. Being a major source of income for local farmers, potato plantation under terracing conditions, rather than on slopes, is strongly recommended as the first choice for achieving the double advantages of erosion control and farmer income. Thirdly, water erosion on gentle slopes was reduced significantly when different CRTs coupled with land-closure treatments (e.g., farmland abandonment, leaving artificial grassland under natural succession, and consecutive fallows) were conducted simultaneously. This result confirms that these measures are effective for conserving soil and water, and are feasible in practice. Finally, water erosion depended significantly on the timing and proportion of rainstorms in certain periods. The sensitivity of water erosion to natural rainfall, however, was also dependent on the specific surface status. In summary, a higher occurrence of rainstorms coupled with crops that have poor resistance to erosion (e.g., potato, flax, and wheat) and up–down cultivation will certainly accelerate runoff and erosion on slopes, whereas natural succession without human disturbance or appropriate CRTs with contour farming practices can markedly reduce water erosion rates.

1. Introduction

Poor land-use systems and extensive cultivation on sloping land are blamed as key contributors to water erosion in many fragile mountainous areas. Such erosion can result in marked reductions in soil fertility and water holding capacity, diminished land productivity, and environmental deterioration (Schiettecatte et al., 2005; Shi et al., 2012; Stavi and Lal, 2011; Wang et al., 2008, 2010). In general, more than 56% of the world's available farmland is endangered by water erosion in agricultural areas, which accounts for 4.3×10^6 km^2 being eliminated for crop production (Jankauskas and Jankauskiene, 2003). Consequently, this situation seriously threatens the agricultural industry, food security, and the sustainability of ecosystem services (Li et al., 2002; Turkelboom et al., 1997). Therefore, the development of more effective cropping systems for fields is important for reducing erosion and protecting the environment (Huang et al., 2003; Li et al., 2002; Shipitalo and Edwards, 1998).

An early and long-lasting cultivation center in ancient China (Wang et al., 2010), the Loess Plateau, which currently suffers from severe drought, erosion, and poverty among farmers, has been regarded as the most environmentally devastated region of the world (Chen et al., 2007; Fu, 1989; Li et al., 2002). The latest data show that the total population in this area has reached 8.74×10^7, nearly 79% of whom are farmers. Total farmland area exceeds 1.3×10^5 km^2. During the past hundreds of years, local residents and communities cleared huge areas of forests and converted them into sloping farmland to increase the food supply (Chen et al., 2007; Fan et al., 2010). Many marginal areas with slope gradients of more than 25° were cultivated, which significantly increased the potential risk of water erosion. The total eroded area of the Loess Plateau was once recorded as 4.54×10^5 km^2, of which 74% was affected by water erosion (YRCC, 1988). Improper

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human activity is estimated to have contributed to more than 46% of the total erosion in the region (Wang et al., 2010; Zhu et al., 2003). The mean erosion modulus (EM) from farmlands was about 8000 t/km^2/year in the late 1990s (Wei et al., 2007). Consequently, water erosion caused by rainstorms and overland flow on steep slopes has accelerated.

The Chinese central government is well aware of the severity of this problem (He et al., 2007; Chen et al., 2010; Fu et al., 2011). In 1999, the so-called "Grain for Green" project, aimed at water erosion control and environmental improvement, was launched. A key part of this program is the restriction of cultivation on slopes with gradients of more than 25°and the conversion of huge marginal areas to forest, shrub, or grassland (Chen et al., 2007; Fan et al., 2010). However, total discontinuation of cultivation on relatively steep slopes of less than 25° or total replacement slopes with terraces was hindered by local food requirements and complex landforms. Thus, large areas of sloping cropland remain and continue to contribute to runoff and sediment yield. For example, Fu et al. (2011) highlighted that zones with gradients from 8° to 35° have accounted for 82% of the total soil loss on the Loess Plateau. The mean EM in areas with gradients ranging from 8° to 25° has been approximately 4150 t/km^2/year, far beyond the tolerable EM of 1000 t/km^2/year promulgated by the Ministry of Water Resources (SL190-96). Unfortunately, in this region, less attention has been paid to water erosion related to cultivation on gentle slopes, a circumstance that should be improved with further steps.

The extent of water erosion on sloping arable lands is affected by many characteristics of the ground surface. Crop rotation, tillage practices, and other field management strategies have key effects over time and space (Lafond et al., 2006; Li et al., 2002; Prasuhn, 2012; Wang et al., 2010). Specific crop species also affect soil conservation (Baets et al., 2011; Malik et al., 2000; Singh et al., 1999). For example, fallow land and land with winter cereal crops have been found to be less susceptible to soil erosion than land cropped with potato or maize (Stevens et al., 2009). Crop rotation types (CRTs) with appropriate field treatments such as conservation tillage have been shown to be valid measures for minimizing erosion, improving water use efficiency and soil carbon sequestration, and maintaining high grain yields (Freebairn et al., 1993; Raclot and Albergel, 2006; Thierfelder and Wall, 2009). Additionally, consecutive plant succession without human disturbance can increase water infiltration and reduce erosion potential significantly, thus improving soil attributes and promoting crop productivity (Kellison and Young, 1997; Xu et al., 2008).

Natural rainfall conditions, on the other hand, are a key driver of water erosion in the real world (de Lima and Singh, 2002; Sasal et al., 2010; Wei et al., 2009). The distribution of rain events in many areas results in only a few storms being responsible for the majority of erosion (Wei et al., 2009). A case study in Tunisia also indicated that three storm-induced floods were responsible for half the sediment yield in 1994 and 2002 (Albergel et al., 2005). The amount, intensity, and regime of natural rain events markedly affect the temporal distribution and magnitude of erosion rates, particularly in fragile ecosystems and on sparsely vegetated slopes (Basic et al., 2004; Thomas et al., 2011; Wei et al., 2007). Consequently, studies on the response of water erosion to crop rotation and rainfall are required in the hilly loess area, especially on hillslopes with gradients of 0° to 25°, where intensified agriculture practices remain in some regions. The combined effects of time-dependent rainfall and the state of fields with respect to cultivated crop, tillage, and soil looseness are important factors in erosion dynamics in any given region (Fiener et al., 2011; Prasuhn, 2012).

In this study, 21 experimental plots with gradients of less than 25° (10°, 15°, and 20°) were established on a rain-fed agricultural catchment in the western part of the Loess Plateau, China. Eight years of consecutive hydrology–erosion data were analyzed. Three specific objectives were expected to be achieved: (1) an analysis of the effect of the features of rainfall on variation in erosion, (2) an assessment of the effects of different crop species and field treatments on runoff and soil erosion, and (3) a determination of the roles of CRSs on water erosion dynamics under gentle-slope conditions.

2. Materials and methods

2.1. Study area

Field experiments were conducted in a typical semiarid area called the Quanwangou catchment (35°22′–35°25′N, 104°31′–104°34′E), which has an area of approximately 9.17 km^2, on the Loess Plateau, Dingxi, northwestern China (Fig. 1). Rain-fed agriculture is the dominant industry in this region, which has experienced accelerated soil erosion for many decades (Chen et al., 2007; Fu, 1989; Huang et al., 2005; Wei et al., 2009). The region has a temperate terrestrial climate with warm, humid summers and cold, dry winters. The mean annual precipitation is 415 mm, more than 60% of which occurs between June and September. The historical highest and lowest annual precipitation amounts are 722 mm (1967) and 246 mm (1982), respectively, which indicates that high temporal variation of precipitation occurs through different years. The average annual sunshine, radiation duration, and air temperature are 5.6×10^9 J/m^2, 2500 h, and 6.2 °C, respectively. The mean annual potential evaporation is 1318 mm. Approximately 140 days/year are frost-free.

Based on a local investigation, more than 70% of the catchment area has been cultivated with a large majority of cereal crops, with which CRTs with leguminous or tuber crops have sometimes been used. The major cultivated crop species are potato (*Solanum tuberosum* L.), maize (*Zea mays* L.), flax (*Linum usitattissimum* L.), and spring wheat (*Triticum aestivum* Linn.). Potatoes grow well and are planted over large areas. Consequently, Dingxi City is known as the "potato capital" of China. Shrubs and grasses, rather than tree species, are more suitable in this area because of the scarce rainfall and restricted freshwater (Chen et al., 2007). Mesquite species, such as sea buckthorn (*Hippophae rhamnoides* L.) and *Caragana korshinskii*, have been planted or sowed as major shrubs, whereas Chinese pine (*Pinus tabuliformis* Carr.), Chinese arborvitae (*Platycladus orientalis* L.), and apricot (*Prunus armeniaca* L.) have been established at the bottom of gullies where better water and nutrient conditions occur. Naturally established and artificially planted grass species include bunge needlegrass (*Stipa bungeana* Trin.), alfalfa (*Medicago sativa* L.), sweet clover (*Melilotus officinalis* L.), and sainfoin (*Onobrychis viciaefolia* Scop.).

The local loess soil (windblown silt) in the small Gaoquangou catchment remains generally the same. Soil depth ranges from 40 m to 100 m, and the soil is classified as calcic Cambisol (FAO–UNESCO, 1974). The depth of arable soil varies from 2 m to 10 m, and soil organic matter is generally less than 10 g/kg. Soil porosity, pH value, available nitrogen, and available phosphorus are 48.5% to 57.3%, 7.5 to 8.6, 30 mg/kg to 60 mg/kg, and 1.3 mg/kg to 2.9 mg/kg, respectively. The mean bulk density of the soil in the top 2 m of the soil layer is approximately 1.1 g/m^2 to 1.4 g/m^2, which renders it vulnerable to water erosion during severe rainstorms and overland flow. Moreover, the landform of the catchment is fragmented and consists of rugged landscapes, with a gully density of 2.38 km/km^2. Altitude varies from 2056 m to 2447 m. Ridges, hillslopes, terraces, and gullies cover an area of 6.9%, 52.4%, 13.8%, and 26.9%, respectively. Slope gradients of 5°, 5–10°, 15–25°, 25–35°, and 35–45° represent 32.3%, 38.8%, 17.3%, 6.1%, and 5.5% of the landscape, respectively. Large amounts of fertile soil are prone to being washed away, which severely degrades the land.

2.2. Experimental design

In this study, 21 experimental plots (Table 1) were established in the middle position of a hillslope within the catchment. The area covered by each bounded plot was 10 m^2, width of 2 m and length of 5 m. For each plot, cement ridges (35 cm above the ground) were constructed at the borders to isolate runoff and sediment