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Impact of tillage erosion on water erosion in a hilly landscape

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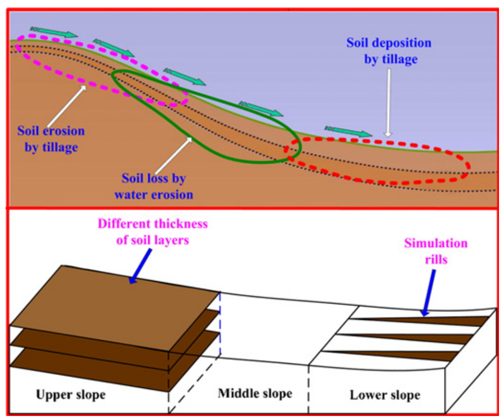
HIGHLIGHTS

- Soil and water losses tended to increase with increasing tillage intensity.
- Tillage erosion effects on water erosion were closely related to tillage intensity.
- Tillage erosion increased soil erodibility and delivered the soil for water erosion.
- Significant changes in hydrodynamic parameters occurred close to field boundaries.

GRAPHICAL ABSTRACT



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ABSTRACT

Little has been known of the interaction between tillage erosion and water erosion, while the two erosion processes was independently studied. Can tillage-induced soil redistribution lead to exaggerated (or retarded) runoff flow and sediment concentrations in steeply sloping fields? A series of simulated tillage and artificial rainfall events were applied to rectangular runoff plots (2 m × 8 m) with a slope of 15° to examine the impacts of tillage erosion intensities on water erosion in the Yangtze Three Gorges Reservoir Area, China. Mean flow velocity, effective/critical shear stress, and soil erodibility factor *K* were calculated to analyze the differences in hydrodynamic characteristics induced by tillage. Our experimental results suggest that mean runoff rates were 2.26, 1.19, and 0.65 L min^{-1} and that mean soil detachment rates were 1.53, 1.01, and 0.61 g m^{-2} min^{-1} during the 70-min simulated rainfall events for 52-, 31-, and 10-year tillage, respectively. A significant difference ($P < 0.05$) in cumulative detachment amounts was found among different tillage intensities. Compared with the soil flux of 0 kg m^{-1}, cumulative detachment amounts for the soil fluxes of 9.86 and 24.72 kg m^{-1} increased by 40.02% and 100.94%, respectively, during the 30-min rainfall event. The results imply that soil and water losses tended to increase with increasing tillage intensity. A significant difference in mean flow velocity occurred near the upper and lower slope boundaries of the field, while significant differences ($P < 0.05$) in runoff depth and effective shear stress were observed among different slope positions. Soil erodibility factor *K* for the soil fluxes of 9.86 and 24.72 kg m^{-1} were 2.40 and 5.11 times higher, respectively, than that for the soil flux of 0 kg m^{-1}. As tillage intensity increased, critical shear stress trended to gradually decrease for all soil fluxes. Our results indicate that

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tillage erosion increases soil erodibility and delivers the soil for water erosion in sloping fields, accelerating water erosion.

1. Introduction

Soil erosion is a serious environmental threat to the sustainability and productive capacity of agriculture. Nearly one-third of the world's arable land has been lost due to soil erosion at a rate of more than 10 million ha per year (Pimentel et al., 1995). Land use change and intensification have resulted in accelerated rates of soil erosion in many areas of the world. Traditionally, soil erosion by water, wind, and gravity has been considered the only driving forces of soil redistribution. While the importance of water erosion is widely recognized, tillage erosion is also known as an important component of total soil erosion in some soils. Tillage erosion rates can be as high (or higher) as (or than) water erosion rates in hilly croplands, which rely on soil erodibility (Blanco and Lal, 2008). Numerous studies on soil redistribution have been conducted on long hillslopes, such as those in North America and Europe, and have reported that soil redistribution is not only controlled by water and wind erosion, but also by tillage erosion (Lindstrom et al., 1992; Govers et al., 1994; Lobb et al., 1995; De Alba, 2001). Tillage erosion is a gradual downslope transport or displacement process caused by long-term tillage operations that notably change soil properties and negatively influence water fluxes, soil-water-plant relations, soil quality and productivity, and other dynamic processes in agricultural landscapes.

As more attention is paid to tillage erosion, a number of studies have established the relationship between tillage erosion and soil properties using physical tracers (Thapa et al., 2001; Zhang et al., 2009), chemical tracers (Zhang et al., 2006; Wang et al., 2014), modelling and field investigations (Wright et al., 2007; Li et al., 2008). With an increase in relevant research, there is a common view that erosion by tillage occurs at upper slope positions, while deposition by tillage occurs at lower slope positions within a hilly landscape. Thus, tillage erosion modifies the spatial patterns of landform elements while inducing changes in soil properties. Recent studies have unravelled interactions among differing scenarios of slope gradients, and tillage operations (e.g., direction, depth, speed), tillage methods (e.g., hoeing, chisel plow, animal traction), and soil properties (e.g., soil constituent, soil aggregation) that affect the magnitude of tillage erosion under either controlled or field-management systems (Li et al., 2008; Wildemeersch et al., 2014; Wang et al., 2014, 2015). However, few studies have demonstrated the effects of tillage erosion on other processes of soil erosion (e.g., water erosion).

In the Three Gorges Reservoir Area, southwestern China, water erosion was once generally assumed to be a unique process of soil redistribution. Recent studies have confirmed that tillage erosion is also a critical process of soil redistribution (Zhang et al., 2006, 2014), with an average tillage erosion rate of 78 Mg ha^{-1} $year^{-1}$ (Zhang et al., 2009). In hilly landscapes, the most intensive erosion by water usually occurs at middle to low backslopes, yet soil movement by tillage is most severe at the upper slope positions (Govers et al., 1996). Strong interactions may exist between water erosion and tillage erosion. These interactions were first identified by Lobb et al. (1995), and they have been the subject of theoretical research since (Lobb et al., 2004; Poesen et al., 2003). There is a shortage of data with respect to hydrodynamic parameters and soil erodibility dynamics in sloping field systems where both water and tillage erosion are important processes of soil redistribution.

The processes of water and tillage erosion have been independently studied so far. Few studies have been conducted on the interaction between tillage erosion and water erosion. It is important to examine the linkages and interactions between both erosion processes, as soil redistribution by tillage may cause the variability of soil hydrodynamic properties across the landscape. In this context, the objectives of this study were to (i) examine the impacts of tillage erosion on runoff rates and sediment concentrations; and (ii) elucidate the variations in hydrodynamic parameters and soil erodibility due to different tillage intensities within the landscape.

2. Materials and methods

2.1. Study sites

The study sites were selected in Zhongxian (in middle part of Chongqing Municipality, Southwest China: 108°10′ E, 30°24′ N) (Fig. 1), located in the Upper Yangtze River Basin in China. The mean annual temperature is 19.2 °C, and the mean annual precipitation is 1150 mm. The cultivated hillslopes are characterized by thin soil layers (generally 50 cm, underlain by rock), great slope gradients, and small patches. The parent material at the study sites is derived from Jurassic sandstone and mudstone, and the subsequent soils are classified as Orthents (Soil Survey Staff, 1994), or Orthic Regosols in the FAO Taxonomy (FAO, 1998). In tillage practices, hoeing always starts at the bottom of the slope segment and step-wise moves upslope; however, at every step, tillage direction is always downslope (i.e., always pulling down). In most cases, the crop rotation includes wheat (*Triticum aestivum* L.), rape (*Brassica napus* L.), maize (*Zea mays* L.), and sweet potatoes [*Ipomoea batatas* (L.) Lam. var. *batatas*].

2.2. Experimental design

The experiments were conducted in the summer of 2014. The treatments of different tillage periods and soil fluxes (the soil transport rate per unit width in the tillage direction along a hillslope profile, i.e., kg m^{-1}) were designed within runoff plots (2 m wide and 8 m long), with an average gradient of 15°, located at the Station of Soil Erosion and Non-point Pollution Observatory in the Three Gorges Reservoir Area, Chinese Academy of Sciences (CAS). Runoff flowed into a rectangular cement trough at the bottom of the plot and was then directed to the outlet point and collected. The selected soil properties of runoff plots are listed in Table 1. The soil depth tended to gradually increase from the upper to lower slope positions (average: 50 cm deep). The mean pH and bulk density of the soil were 7.12 and 1.28 g cm^{-3}, respectively, with an average of 49.62% sand, 38.62% silt, and 11.73% clay.

2.2.1. Tillage-duration treatment

The most obvious example of tillage erosion is the gradual removal of topsoil by tillage and the subsequent decrease in the thickness of soil profiles at the upper slope positions of steep lands. Thus, we designed four types of soil profiles with different depths (bedrock exposure, 10, 20, and 45 cm deep) at the upper slope positions (0–3 m) of the runoff plots to represent different tillage intensities (Fig. 2A). A plastic sheet was used to cover the surface of runoff plots at the upper slope positions to represent the bedrock exposure by long-term tillage. Additionally, we dug out the soil of 10 cm and 20 cm in depth, respectively, from the upper slope positions of runoff plots. Then, a plastic sheet was placed on the surface of exposed soils, and the soil was backfilled to the plot and packed to its original bulk density. These treatments were considered as soil depths of 10 cm and 20 cm at the upper slope positions, while the original runoff plot (i.e., 45 cm deep at the upper slope positions) was considered the control (CK).