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Effects of soil type and rainfall intensity on sheet erosion processes and sediment characteristics along the climatic gradient in central-south China

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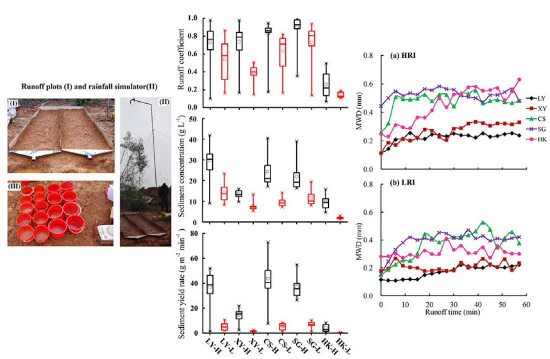
HIGHLIGHTS

- Soil type impact on sheet erosion was investigated by field plot experiments.
- Illite content was negatively correlated with average runoff coefficient ($p < 0.05$).
- Amorphous iron oxides and bulk density enhanced soil resistance to erosive forces.
- Sediment size generally increased from temperate Luvisol to tropical Ferralsol.
- This study facilitated a better understanding of the climate effect on soil erosion.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil erosion poses a major threat to the sustainability of natural ecosystems. The main objective of this study was to investigate the effects of soil type and rainfall intensity on sheet erosion processes (hydrological, erosional processes and sediment characteristics) from temperate to tropical climate. Field plot experiments were conducted under pre-wetted bare fallow condition for five soil types (two Luvisols, an Alisol, an Acrisol and a Ferralsol) with heavy textures (silty clay loam, silty clay and clay) derived separately from loess deposits, quaternary red clays and basalt in central-south China. Rainfall simulations were performed at two rainfall intensities (45 and 90 mm h^{-1}) and lasted one hour after runoff generation. Runoff coefficient, sediment concentration, sediment yield rate and sediment effective size distribution were determined at 3-min intervals. Runoff temporal variations were similar at the high rainfall intensity, but exhibited a remarkable difference at the low rainfall intensity among soil types except for tropical Ferralsol. Illite was positively correlated with runoff coefficient ($p < 0.05$). Rainfall intensity significantly contributed to the erosional process ($p < 0.001$). Sediment concentration and yield rate were the smallest for the tropical Ferralsol and sediment concentration was the largest for the temperate Luvisol. The regimes (transport and detachment) limiting erosion varied under the interaction of rainfall characteristics (intensity and duration) and soil types, with amorphous iron oxides and bulk density jointly enhancing soil resistance to erosive forces (Adj-$R^2 > 88\%$, $p < 0.001$). Sediment size was dominated by <0.1 mm size fraction for the Luvisols and bimodally distributed with the peaks at <0.1 mm and 1–0.5 mm size for the other soil

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types. Exchangeable sodium decreased sediment size while rainfall intensity and clay content increased it (Adj-$R^2 = 96\%$, $p < 0.01$). These results allow to better understand the climate effect on erosion processes at the spatial-temporal scale from the perspective of soil properties.

1. Introduction

Soil erosion is the most widespread form of land degradation and has posed a major threat to the sustainability of natural ecosystems (Lal, 2001; Dlamini et al., 2011). Sediment losses are usually associated with organic matter, nutrients, heavy metals, pesticides and other contaminants, resulting in direct or indirect impact on on-site and off-site soil functions, aquatic, terrestrial and atmospheric ecosystems (Mchunu and Chaplot, 2012; Glendell and Brazier, 2014; Rickson, 2014). Soil erosion by water involves the processes of detachment, transport and deposition of soil particles or aggregates (Ellison, 1947). Understanding erosion processes and determining the controlling factors are necessary for erosion control and development of erosion prediction models.

Rainfall erosion generally results from the individual or combined action of raindrop impact and surface flow (Kinnell, 2005) and is influenced by many factors such as rainfall characteristics (rainfall intensity, duration and pattern), soil properties (soil texture, aggregate stability, bulk density, clay mineralogy and organic matter) and surface conditions (slope, vegetation cover, roughness, the type and extent of crust) (Martínez-Mena et al., 2002; Lado and Ben-Hur, 2004; Le Bissonnais et al., 2005; Malam Issa et al., 2006; Ran et al., 2012; Mahmoodabadi and Sajjadi, 2016; Wang et al., 2017). Among these factors, raindrop impact is an important erosive force, not only detaching soil materials but also enhancing sediment transport by overland flow (Zhang and Wang, 2017) while soil properties especially aggregate stability affect soil detachability and water infiltration (Le Bissonnais, 1996). The actual effects of rainfall intensity on erosion process vary with soil properties or soil type (Martínez-Mena et al., 2002; Asadi et al., 2007; Defersha and Melesse, 2012). For example, Martínez-Mena et al. (2002) reported that the predominant erosion processes in the calcareous colluvial soil and marl soil were dependent on and independent of rainfall intensity, respectively. Defersha and Melesse (2012) found that sediment concentration decreased with the increase of rainfall intensity for clay Vertisol, but it showed an opposite trend for the clay Cambisol and sandy clay loam Regosol. The interactions between soil properties and rainfall characteristics affect erosion processes through altering surface conditions such as crust that reduces water infiltration and soil detachability (Le Bissonnais et al., 2005; Carmi and Berliner, 2008; Mahmoodabadi and Sajjadi, 2016; Vaezi et al., 2017). As the crust matures, transition occurs from a transport capacity-limited system to a detachment-limited system in sediment delivery (Moore and Singer, 1990). The erosion processes generally vary in time and space due to the dynamic evolution of soil surface conditions during the rainfall event (Le Bissonnais et al., 2005; Kinnell, 2005; Wang et al., 2013).

Besides runoff and sediment yield, sediment size characteristics and temporal variation, especially the effective size of sediments, are necessary for a better quantification of sediment transport mechanism and rate (Asadi et al., 2007, 2011; Shi et al., 2012; Wang et al., 2014; Hancock et al., 2017). Kinnell (2005) summarized six sediment transport models: raindrop splash, raindrop-induced saltation, raindrop-induced rolling, flow-driven saltation, flow-driven rolling and suspension, all of which depend on sediment properties (size, density and shape) and flow hydraulic characteristics (depth, velocity and turbulence) (Kinnell, 2006, 2012; Asadi et al., 2011; Shi et al., 2012). Coarse material is transported as rolling or saltation while the fine material remains suspended (Kinnell, 2006). As flow velocity increases, the dominant transport modes change from raindrop-induced rolling/saltation to flow-driven rolling/saltation (Kinnell, 2005; Asadi et al., 2007). Asadi et al. (2007, 2011) reported that the bimodal distribution of sediment size resulted from the two transport mechanisms of rolling and suspension/saltation in the coarser and finer size classes, respectively. The sediment properties are usually inherited from original soils and thus vary with soil types (Martínez-Mena et al., 2002; Malam Issa et al., 2006; Asadi et al., 2007; Wang et al., 2014). Compared to sediment amount, less research attention has been paid to the sediment size distribution, let alone at the field scale.

To date, most studies are focused on the climate effect on soil erosion mainly in terms of precipitation, vegetation and land use (Cerdà, 1998; Nearing et al., 2004; Ruiz-Sinoga and Diaz, 2010; Serpa et al., 2015) and few efforts have been made to investigate erosion processes response to climate change from the perspective of soil properties or types (Salvador Sanchis et al., 2008). As an indicator of soil resistance to erosion, aggregate stability has been verified to be influenced by soil type or climate condition (Six et al., 2002; Wu et al., 2016). Soil erodibility widely used in empirical models (USLE or RUSLE) for various soil types is generally applicable to predict the long-term average soil loss and that in the process-based models (WEPP) is mainly based on soil texture, both of which do not take into account the temporal variations during the rainfall events (Kinnell, 2005, 2017; Wang et al., 2013). In addition, despite intensive experiments performed on the erosion of various types of soils, these data cannot explain the general mechanism underlying erosion processes due to the incomparability of experimental conditions (Malam Issa et al., 2006; Knapen et al., 2007; Gumiere et al., 2009; Kinnell, 2016). Therefore, a systematic investigation with field experiments, although costly and laborious, is necessary for a better understanding of the specific erosion processes of different types of soils.

The main objective of this study was to investigate the effects of soil type and rainfall intensity on sheet erosion processes (hydrological, erosional response and sediment size characteristics) along the climate gradient. It is hypothesized that the susceptibility of surface soils to rainfall erosion varies with the physicochemical nature of soils which mainly results from climate conditions and that there exists a significant difference in sediment sizes and transport mechanisms among different soil types. In this study, field plot rainfall simulation experiments were conducted on bare fallow soils with an increased weathering gradient from temperate to topical climate. When isolating the effects of soil type and rainfall intensity on sheet erosion, the factors such as plot size, land use, slope gradient, soil texture, profile constitution and soil surface conditions were maintained as uniform as possible.

2. Materials and methods

2.1. Experimental sites and soils

Based on the principle of typicality of soil types and accessibility of field rainfall simulation, five typical soils were selected and the experimental sites were separately located in Luoyang city (LY) in Henan province, Xiangyang city (XY) in Hubei province, Changsha city (CS) in Hunan province, Shaoguan city (SG) in Guangdong province, and Haikou city (HK) in Hainan province from north to south in central-south China (Fig. 1-a). The experimental sites fall separately into the warm temperate, northern subtropical, mid-subtropical, southern subtropical and tropical region and in East Asian Monsoon climate with the mean annual precipitation ranging from 650 to 1778 mm and the mean annual temperature from 13.7 to 24.2 °C. In this study region, water erosion