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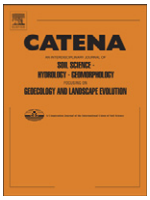

An interaction between vertical and lateral movements of soil constituents by tillage in a steep-slope landscape

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ABSTRACT

The interaction between vertical and lateral movements of soil constituents by tillage needs to be addressed to better understand the transfer processes of soil constituents on a hillslope. In this experiment, traditional tillage by consecutive hoeing during a few days and the cesium-137 (^{137}Cs) tracing were performed in the Sichuan Basin, China to demonstrate direct effects of intensive tillage on the vertical redistribution of soil constituents and the interaction between vertical and lateral transfers of soil constituents. The changes in ^{137}Cs residual rates showed that intensive downslope movement of soil by tillage occurred along the transect of slopes, and the lateral transfer of those soil constituents proceeded in the same direction as the soil movement by tillage. The vertical transfer patterns differed from one another for the upper, middle, and lower slope positions. At the upper slope positions, intensive tillage notably decreased the concentrations of soil organic carbon (SOC) and total nitrogen (TN) in the whole soil profile. At the middle and lower slope positions, SOC concentrations in the surface soil layer (0–15 cm) markedly declined after intensive tillage, suggesting that the downslope movement of soil by tillage translocated the soil with low concentrations of SOC and TN derived from upslope towards the middle and lower slopes. The decreases in SOC and TN of the surface soil exerted an important impact on the underlying soil near the surface soil due to the vertical transfer of soil constituents by mixture effects of tillage. Significant changes in the depth distribution pattern of soil constituents by intensive tillage occurred close to the upslope and downslope boundaries of the field Our results revealed that the vertical movement of soil constituents interacted with their downslope movement under intensive tillage, which resulted in a chain transfer process of soil constituents: effects of the vertical transfer at all landscape positions on the lateral transfer along the transect of slopes, and conversely, effects of the lateral transfer on the vertical transfer.

1. Introduction

It is well known that soil erosion is a major environmental threat to the sustainability and productive capacity of agriculture. Each year, 75 billion metric tons of soil are removed from the land by soil erosion (e.g., water, wind, tillage erosion), with most coming from steeply sloping fields (Wei and Li, 2006). Accelerated soil erosion by intensive tillage on the hillslope is a major threat to sustainable agricultural production as well as environmental sustainability. Tillage erosion is the gradual soil displacement downslope caused by hoeing or plowing. The adverse influences of tillage erosion on agricultural environment have drawn more and more attention of soil workers worldwide. In recent years, particularly in specific landscape units within the context of non-mechanized agriculture, tillage erosion has become an important component of total soil erosion in hilly croplands. Between 15 and 600 Mg ha^{-1} of soil was lost by tillage erosion annually in hilly croplands (Govers et al., 1994; Thapa et al., 1999; Zhang et al., 2004), showing an extremely severe soil loss by successive tillage. The studies suggested that tillage erosion can represent as much as 70% of total erosion on shoulder slope landscape positions in the topographically complex upland regions of south–western Ontario, Canada and in short slope landscape of hilly areas of Sichuan, China (Lobb et al., 1999; Zhang et al., 2012). Intensive tillage operations destroy the structure of natural soils, overturn and drag the loose material, and redistribute soil downslope towards the lower slope positions.

Cesium-137 (^{137}Cs) is an artificial radionuclide produced from nuclear fission from the 1950s to 1970s (with a maximum deposition rate in 1963) and resulted from the Chernobyl accident at the Chernobyl nuclear power plant on 26 April 1986. However, the impact of Chernobyl accident has been limited to the Black Sea and some regions in the North Atlantic (De Cort et al., 1998; Golosov et al., 2013). Its use as a tracer for soil redistribution by erosion and sediment provides an alternative approach to document rates and overcomes many of the problems associated with conventional methodologies (Mabit et al., 2008). Cesium-137 is a useful tracer for investigating soil redistribution

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because it is rapidly and strongly adsorbed by fine particles in soil surface horizons when it is deposited in the ground (Walling and Quine, 1991; Ritchie and McCarty, 2003; Lacoste et al., 2014; Quijano et al., 2016), and its subsequent redistribution reflects the physical processes associated with water, wind, and tillage erosion (Govers et al., 1999). In cultivated soils, ^{137}Cs is evenly mixed in tillage layers due to successive tillage, and its consequent movements coincide with the associated soil or sediment particles. Therefore, the ^{137}Cs spatial distribution on hillslopes usually reflects the net influence of soil redistribution in soil profiles.

An increasing number of studies have demonstrated the effects of tillage on the transfer of soil constituents. To recognize the redistribution processes of soil constituents has important implications for understanding the variation in soil properties within a landscape. Most of the relevant studies have focused on understanding the influences of tillage erosion on soil constituent redistribution along the transect of the slope (Li et al., 2008; Li et al., 2013; Chen et al., 2014), but little is known about the long-term influences of tillage on the vertical transfer of soil constituents in specific landscape units. A diffusion tillage translocation model, proposed by Li et al. (2008), has been used by investigators to simulate the tillage transport process in the tillage layer and the sublayer at soil accumulation positions. Van Oost et al. (2000) reported the use of a convoluting procedure to establish a model for predicting soil constituent redistribution, but no data were provided on the transport of surface soil and subsoil at the different landscape positions. As a result, the redistribution pattern of soil constituents needs to be verified in the actual situation. To examine the redistribution of soil constituents by tillage, both the lateral redistribution of soil and the vertical effect in different landscapes should be taken into account. Against this background, the objectives of this study were (1) to examine impacts of intensive tillage on vertical and lateral soil redistribution by ^{137}Cs data and ^{137}Cs residual rates; and (2) to elucidate the interactions between vertical and lateral transfers of soil constituents under unidirectional downslope tillage within the context of non-mechanized agriculture.

2. Materials and methods

2.1. Study sites and experimental treatments

The study site lies in Jianyang County in the east of Sichuan Basin (30°26′N, 104°28′E) where the hills with elevations 400–587 m a.s.l. account for 88% of the whole region (Wang et al., 2014). The average annual rainfall is 872 mm, of which approximately 90% is received during the rainy season (May to October). In the study area, soils derived from purple mudstone in the Jurassic Age were classified as Orthents (Soil Survey Staff, 1994). The soil texture is loam with 9.65–10.96% clay, 42.06–49.32% silt, 39.72–48.29% sand. Soil layers in the summit segments of the slope are quite thin (commonly 20 cm over bedrock), whereas thicker soil layers are present at the toeslope position (commonly 50 cm or so over bedrock). The study area is one of the most important grain-growing areas in the Sichuan Basin where more than four-fifths of the people still depend on farming. In most cases, the crop rotation system includes wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and sweet potato (*Ipomoea batatas* (L.) Lam. var. *batatas*).

A linear slope was selected as the study site, and was divided into the two adjacent small plots along the slope transect, and tillage treatment and sampling were performed in each of the two plots, respectively. In tillage practices by hoeing, the farmer is used to beginning at the bottom, and going to the top of the slope, with the tilled soil always moving downslope due to drag and gravity. The plot had a horizontal length of 21 m and a width of 5 m, with an average gradient of 18%. To investigate the impact of long-term tillage on soil constituents across the landscape, we conducted a successive tillage experiment with a tillage depth of 15 cm to simulate the tillage translocation process. Successive tillage was performed 20 times in a short time interval (3 days) over which no rainfall occurred, thereby avoiding the influence of other processes of soil erosion (e.g. water erosion) on soil redistribution. And we used the ^{137}Cs radionuclide as a tracer of tillage erosion to assess the direction and magnitude of soil redistribution in the landscape.

2.2. Soil sampling and analysis

Soil samples were taken along the two sampling lines of the slope with a contour distance of 2 m in September 2012. The entire slope was divided into the upper slope (0–7 m), middle slope (8–15 m), and lower slope (16–21 m) from the hilltop to bottom. The elevation and coordinate of each sample point were measured using a survey-grade Differential Global Positioning System (DGPS). Four soil profiles were taken to collect samples for each slope section, i.e., two profiles along a sampling line within each slope section. Soil profile sampling for ^{137}Cs, soil organic carbon (SOC), total nitrogen (TN), and calcium carbonate ($CaCO_3$) was carried out along the slope at each slope position with an 8 cm diameter hand-operated core sampler, going down to the bedrock at each sample point. Core samples with two repetitions were taken and divided into subsamples with 5 cm depth increments from the soil surface to bedrock, which were then bulked to make a composite subsample.

Soil samples were air-dried, crushed, and passed through a 2 mm mesh sieve to filter out coarse materials. Samples of the <2 mm particle size fraction were weighed and then packed into plastic beakers for subsequent analyses. The ^{137}Cs activity was detected with a hyperpure lithium-drifted germanium spectrometer coupled with Nuclear Data 6700 multichannel analyzer with an average counting time of over 30,000 s and a sampling weight of 300 g. The original ^{137}Cs concentration per unit mass basis (Bq kg^{-1}) was converted into the inventory (Bq m^{-2}) using the total mass of the bulked core sample and the cross-sectional area of the sampling core. The determination of SOC concentrations was carried out using wet oxidation with $K_2Cr_2O_7$, and TN was determined with the classical Kjeldahl digestion method (Liu, 1996). Calcium carbonate concentrations of soils were measured as CO_2 by a pressure-calcimeter method (Liu, 1996).

2.3. Calculation of the ^{137}Cs residual rate

The ^{137}Cs percentage residual of the soil profile was calculated to obtain the net soil redistribution ratio (Quine and Zhang, 2002). Relative to soil redistribution rates by the mass balance models (Walling and He, 1999; Tosic et al., 2012), this method yields low accuracy, but makes no assumptions regarding erosion process and erosion rate calculation. The ^{137}Cs residual rate can be expressed as:

$$C_r = 100 \cdot (C_p - C_f)/C_f \quad (1)$$

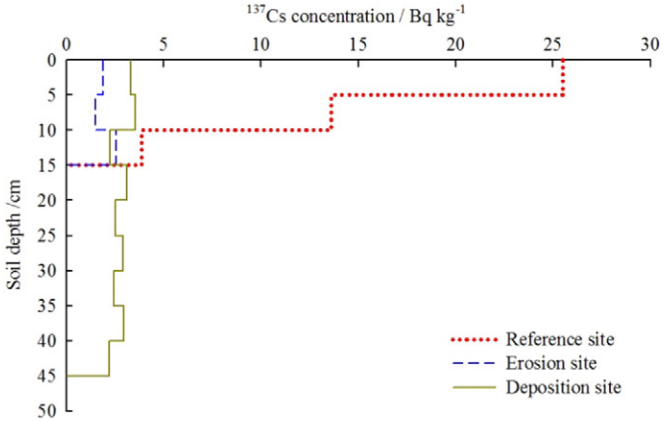

Fig. 1. Typical depth distribution of ^{137}Cs concentrations at the erosion, deposition, and reference sites.