Forms and Fluxes of Soil Organic Carbon Transport via Overland Flow, Interflow, and Soil Erosion

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The contributions of hydrological pathways (including overland flow, interflow, and soil erosion) to lateral soil organic carbon (SOC) transport have remained unclear until now. Hillslopes were monitored using free-draining lysimeters (8 m by 4 m) to quantify dissolved organic carbon (DOC) losses due to overland flow and interflow and the total organic carbon (TOC), water extractable organic carbon (WEOC), particulate organic carbon (POC), and mineral-associated organic carbon (MOC) fractions in sediments from sloping croplands containing Regosols in Southwest China. The average annual DOC losses due to overland flow and interflow were 158.8 ± 33.0 and 750.4 ± 79.3 mg C m^{-2}, respectively, and the TOC lost with sediment was 2201.0 ± 429.2 mg C m^{-2}. Overland flow, interflow, and sediment accounted for 5, 24, and 71%, respectively, of the annual SOC losses. The average annual DOC, POC, and MOC loss fluxes were 918.6 ± 115.3, 375.2 ± 94.4, and 1816.4 ± 331.8 mg C m^{-2}, respectively. The MOC contents in the sediments were positively correlated with rainfall, and the DOC concentrations in the interflow water were negatively correlated with rainfall. In conclusion, soil erosion is the dominant hydrological route for lateral SOC transport, and interflow is another crucial route that is usually underestimated. Soil organic C is mainly lost in the forms of MOC and DOC, which is an important component of water ecosystems. Therefore, the mitigation of SOC losses would be more effective if soil erosion and interflow conservation practices were adopted together, particularly for Regosols on hillslopes.

Core Ideas

- **Interflow is another crucial route of soil organic carbon lateral transport.**
- **Overland flow, interflow, and sediment contributed 5, 24, and 71%, respectively, of annual loss loads of soil organic carbon lateral transport.**
- **Dissolved organic carbon is another important component for SOC lateral transport.**

Overland flow, interflow, and soil erosion, which commonly occur during natural rainfall events, are three major routes for the lateral transport of SOC from soils to aquatic ecosystems. These routes are known to negatively affect C cycling processes in agricultural ecosystems (Rimal and Lal, 2009; Kindler et al., 2011; Mchunu and Chaplot, 2012). Soil erosion disturbs topsoil and preferentially removes SOC from upslope sites, resulting in the mineralization, redistribution, and burial of SOC in depositional environments (Lal, 2003). Soil organic C leaching via interflow is a physical process that results from the production, adsorption, and desorption of SOC in soils (Kalbitz et al., 2000; Fujii et al., 2009). Meanwhile, the lateral transport of SOC and other forms of organic C (e.g., DOC, POC, and MOC) remarkably affect SOC sequestration and water quality (Dhillon and Inamdar, 2014). Therefore, the forms, fluxes, and lateral transport of SOC must be determined to improve our current knowledge of C loss processes in agricultural ecosystems.

Sediments resulting from soil erosion, which primarily contain semi-stable or stable SOC (i.e., POC and MOC), are usually rich in fine silt and clay-sized particles because soil aggregates provide physical protection for the SOC (Ashagrie et al., 2007; Martínez-Mena et al., 2012). The transport of DOC from the soil to water is analogous to the runoff that links natural rainfall events because it alters the pathways of soil water movement through different soil horizons containing considerable amounts of DOC. Thus, DOC is considered as a major organic C

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fraction in overland flow, interflow, and leaching because of its water solubility (Dawson and Smith, 2007). Over the last 20 yr, several studies have explored sediment organic C losses in agroecosystems (Van Oost et al., 2007; Ciais et al., 2008; Wiaux et al., 2014) and DOC transport via overland flow or leaching in forested and agricultural watersheds (Fröberg et al., 2005; Haaland and Mulder, 2010; Van Gaelen et al., 2014a, 2014b). However, most of these studies only considered the lateral transport of SOC in isolated situations (e.g., through overland flow, leaching, or soil erosion alone), and SOC losses have not been measured simultaneously for these three hydrological routes in arable soils. In addition, few studies have quantified the contributions of lateral SOC transport routes in hillslopes. Consequently, comprehensive, and integrated monitoring should be performed to evaluate the amounts of lateral SOC transport based on field measurements from multiple years to decrease uncertainty when evaluating SOC losses. Moreover, previous studies have shown that the transport of DOC from soils to aquatic ecosystems could enhance the sorption and mobility of pesticides, heavy metals, and nonpoint-source P in surface waters (Kirchman et al., 1991; Li and Shuman, 1997; Li et al., 2005). Although some knowledge of the amount of DOC transport in surface runoff or DOC leaching is available, the export of DOC with interflow (leaching at the soil–bedrock interface) and its contributions to the lateral transport of SOC in hillslopes remain largely unknown.

Covering an area of 160,000 km^2, the hilly region dominated by Regosols is one of the most important agricultural areas in the upper reaches of the Yangtze River (Li et al., 1991) and accounts for 68% of the total croplands in Sichuan Province. Sloping croplands with Regosols are widely distributed throughout the area, are commonly characterized by low SOC levels and are extensively degraded by severe soil erosion due to their terrain and the occurrence of multiple natural rainfall events (Zhu et al., 2012). Regosols are characterized by thin soil layers with an average thickness of 60 cm and are easily saturated by rainwater during precipitation. Interflow is a prevailing phenomenon that occurs during the rainy season (Zhu et al., 2009). In general, overland flow, interflow, and soil erosion occur simultaneously on hillslope croplands during the rainy season. However, no research has measured the lateral transport of SOC via overland flow, interflow, and soil erosion synchronously. Thus, the magnitude of the lateral transport of SOC via these hydrological routes remains uncertain.

In this study, SOC losses via overland flow, interflow, and soil erosion are simultaneously monitored during four rainy seasons from 2009 to 2012. The specific objectives of this study were to (i) quantify the fluxes of DOC loss due to overland flow and interflow; (ii) obtain the fluxes of WEOC, POC, and MOC loss fluxes due to sediment transport, and (iii) estimate the routine contributions of the lateral transport of SOC.

MATERIALS AND METHODS

Site and Soil Description

This experiment was conducted at the Yanting Agro—Ecological Station of Purple Soil located at an altitude of 400 to 600 m in the central Sichuan Basin of Southwest China. The site is located at 31°16′ N. Lat, 105°28′ E. Long. and has a subtropical climate with an annual mean temperature of 17.3°C and a mean precipitation of 836 mm (calculated over the past 20 yr). The spring, summer, autumn, and winter seasons account for 5.9, 65.5, 19.7, and 8.9%, respectively, of the total annual rainfall. The amount of annual precipitation during the experimental period was 985 mm in 2009, 892 mm in 2010, 1061 mm in 2011, and 1080 mm in 2012 (Fig. 1). The soil at the site is classified as a Regosol according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006). Rain-fed farming has been maintained on the soil, with slope gradients of 3 to 15% and a shallow soil layer of approximately 30 to 80 cm. The soil developed from purplish shale and has the typical "binary structure of soil-bedrock" (Xiong and Li, 1986). The specific soil used in this study is a silty loam soil with a pH of 8.3, bulk density of 1.3 g cm^{-3}, organic matter content of 8.8 g kg^{-1}, total N content of 0.6 g kg^{-1}, and saturated hydraulic conductivity of 16.8 mm h^{-1} (Zhu et al., 2009).

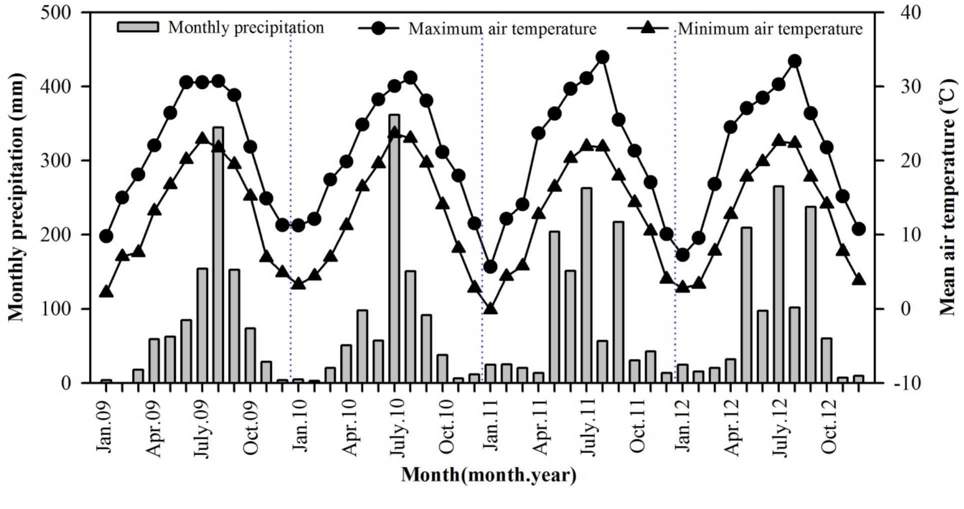

Fig. 1. Monthly precipitation and mean air temperatures during the experimental period (January 2009 to December 2012).

Experimental Setup

The soil profile of the experimental cropland is shallow, with an average depth of 60 cm, and the soil overlies bedrock with poor water conductivity. More than 75% of the annual precipitation occurs during the summer season (from May to October), and the soil profile is easily saturated due to the shallow depth to bedrock. Hence, the soil water content potentially drives overland flow and interflow, which move downward along the slope. Based on the hydrologic characteristics of the hillslope, field runoff plots were designed and constructed as free-draining lysimeters according to the *Handbook of Water and Soil Conservation Monitoring in Runoff Plots and Small Watershed* (Ministry of Water Resources, The People's Republic of China, 2015). The free-draining lysimeters were placed by excavating the soil to the bedrock and were constructed for hydrologic isolation in 2002 (Fig. 2). Soil was backfilled around the lysimeters according to the natural order of the soil profile. After 7 yr of settlement, the soils were considered to reach a near-natural state and no water logged areas occurred along the soil–bedrock interface. Meanwhile, to prevent lateral seepage from adjacent plots, each plot was hydrologically isolated by walls filled with cement that reached the bedrock and extended to a depth of at least 60 cm. These walls were built above the plots and at the lateral edges of the plots. Conflux troughs (Patent: ZL2007100640686) were built at the soil surface and soil–bedrock interface to collect overland flow and interflow (Zhu et al., 2009). The edges of the troughs for collecting overland flow were 10 cm lower than the soil surface to ensure that all the overland flow was collected. The interflow conflux trough was excavated to a depth of 10 cm below the soil–bedrock interface and filled with clean arenaceous quartz and pebbles to the soil–bedrock interface. Containers were installed under each conflux trough to collect water samples from the overland flow and interflow. The plot sizes measured 8 m (length) by 4 m (width), with a slope gradient of 6.5° and a soil depth of 60 cm. The experimental plots were laid out in a randomized block design with three replicates.

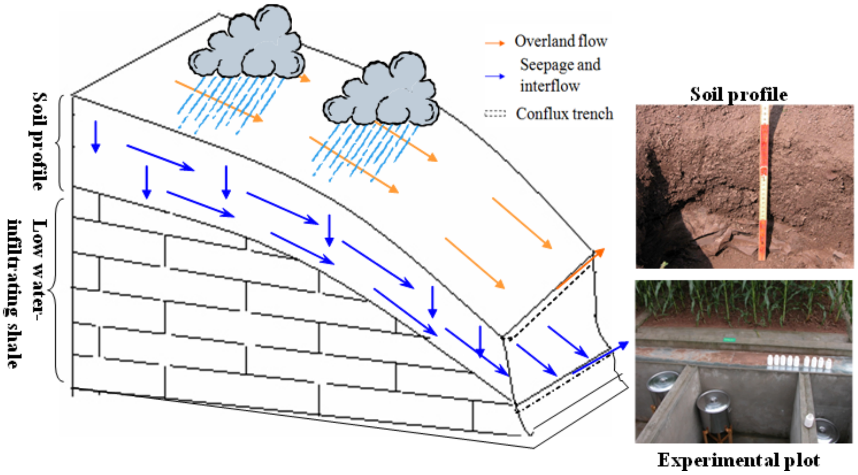

Fig. 2. Schematic illustration of structure of experimental plot on the hillslope cropland of Regosol.

The experimental plots were subjected to conventional winter wheat (*Triticum aestivum L.*) cultivation from late October to May of the following year, followed by a summer maize (*Zea mays L.*) rotation from May through September. In this experiment, wheat was planted in late October and harvested in the middle of May during the following year. The maize crop was planted in early June and harvested in late September. Wheat and maize were harvested manually, and all above-ground biomass, except for the stubble (approximately 5 cm height), was removed from the experimental fields. Synthetic fertilizer was applied once at the beginning of each wheat growing season at rates of 130 kg N ha^{-1}, 39 kg P ha^{-1}, and 30 kg K ha^{-1}, and N was applied at the beginning of each maize growing season at a rate of 150 kg ha^{-1}. This fertilization and crop rotation regime is typical of the region.

Discharge Measurements and Water Sampling

All overland flow and interflow buckets were manually emptied before precipitation. The overland flow and interflow discharge were measured when the water flow completely stopped after each rain event during the experimental period (May 2009–October 2012). Workers were ready to measure water discharge and obtain samples to avoid missing data. The water levels in the buckets were measured using a ruler after every rain event to calculate the runoff discharge. To decrease the error of the manual measurements, the water levels in the buckets were measured four times and the means of the measured water levels were determined. The overland flow and interflow water samples were collected separately from the different buckets during each rain event. Polyethylene bottles (500 mL) were used to collect water samples to determine the DOC concentration after the water levels were measured. To determine the soil erosion rate, the water and sediment in the buckets were completely mixed and a 10-L polyethylene bottle was used to collect a runoff sample. After allowing the samples to settle for 48 h in the collectors, the samples were treated with an $AlK(SO_4)_2 \times 12\ H_2O$ solution to promote coagulation. When the sediment settled, the excess water was decanted, and the remaining soil was dried at 105°C and weighed (Polyakov and Lal, 2008).

Precipitation and Rainfall Intensity Monitoring

The amount of rainfall was monitored using an automatic tipping bucket gauge (R_{13}, Vaisala, Finland). This instrument uses a tipping-bucket mechanism to produce a contact closure when it receives a predetermined small quantity of rainfall (0.2 mm). The rainfall intensity was measured using a siphon rainfall recorder, and the maximum rainfall intensity was obtained using intensity recording paper with a precision of 0.1 mm (Wang and Zhu, 2011).

Analytical Methods

Water samples of the overland flow and interflow were passed through a 0.45-μm filter membranes for DOC analysis, and the DOC concentrations in the filtrates were automatically analyzed using flow injection technology and a special DOC module with an AA3-Auto-analyzer (Bran+Lubbe, Norderstedt, Germany). A fresh 1.5-g sediment sample was shaken in 15 mL of distilled water (1:10 w/v) for 120 min in a 50-cm^3 polypropylene bottle on a reciprocating shaker at 200 rev min^{-1}. Next, the sediment-water mixture was centrifuged at 5000 rev min^{-1} for 30 min and passed through a 0.45-μm filter membrane. The WEOC concentration in the filtrate was automatically analyzed using flow injection technology and an AA_3 Auto-analyzer. The water content of the fresh sediment was measured by drying the sample for 24 h (Lu, 2000). Thus, the sediment WEOC content was measured as described above. The TOC content in the sediment was measured using the wet combustion method in 133 mmol L^{-1} $K_2Cr_2O_7$ at 180°C for 5 min, followed by titration of the digests with $FeSO_4$ (Lu, 2000). The POC content in the sand-sized (0.053~2 mm) soil fraction was determined according to the method described by Cambardella and Elliott (1992). Two grams of air-dried sediment was placed in 20 mL (1:10 w/v) of 5% sodium hexametaphosphate and shaken for 18 h using a reciprocating shaker (90 rev min^{-1}). The soil suspension was poured over a 0.053-mm screen with distilled water to ensure separation. All the material remaining on the screen was washed into a dry dish, oven-dried at 60°C for 48 h, and ground to determine the C content using the SOC analysis method. The MOC content was measured by subtracting the POC and WEOC contents from the TOC in the sediment.

Data Analysis

The flux of the DOC loss during an individual flow (Q_i) produced from a rainfall event was calculated as follows:

$$Q_i = C_i \times q_i \qquad [1]$$

where Q_i is the flux of the DOC loss in the overland flow or interflow (mg m^{-2}); C_i is the DOC concentration in the overland flow or interflow water (mg L^{-1}); and q_i is the runoff depth per unit (mm).

The WEOC, POC, and MOC loss fluxes in the sediments during an individual flow (Q_{Si}) and for each rainfall event were calculated as follows:

$$Q_{Si} = C_{si} \times q_{si} \qquad [2]$$

where Q_{Si} indicates the WEOC, POC, or MOC loss fluxes (mg m^{-2}); C_{si} is the WEOC, POC, or MOC content (mg g^{-1}); and q_{si} is the sediment loss flux (g m^{-2}).

The annual cumulative DOC, WEOC, POC, and MOC loss fluxes were calculated as follows:

$$Q = \sum_{i=1}^{n} Q_i \qquad [3]$$

where Q indicates the annual cumulative loss flux (mg m^{-2}), $i = 1 \sim n$ (n is the number of runoff events in a given year).

The runoff coefficient (RC) for overland flow or interflow was calculated as follows:

$$\text{RC} = q/R \qquad [4]$$

where q is the cumulative runoff depth in overland flow or interflow per unit from May to October (mm) and R is the cumulative rainfall from May to October (mm). The statistical analyses were performed using the SPSS 19.0 software package. Sigma plot 10.0 was used to prepare the graphs.

RESULTS

Hydrological Characteristics and Soil Erosion

In this study, 32 natural rainfall events were observed during four rainy seasons from 2009 to 2012. Each rainfall event resulted in 16.3 to 177.1 mm of rainfall, and the maximum rainfall intensity varied between 1.1 and 60 mm h^{-1} (Fig. 3a). The overland flow discharges ranged from 1.5 ± 0.2 to 53.9 ± 1.2 mm (Fig. 3b). The annual cumulative discharges via overland flow were 54.4 ± 9.3, 43.7 ± 2.2, 59.4 ± 3.6, and 71.7 ± 3.4 mm in 2009, 2010, 2011, and 2012, respectively (average, 57.3 ± 4.6 mm). The annual cumulative interflow discharges were 111.4 ± 11.4, 269.6 ± 5.2, 299.1 ± 3.9, and 299.6 ± 7.1 mm in 2009, 2010, 2011, and 2012, respectively (average, 244.9 ± 6.9 mm), and the average RC for overland flow and interflow during the 4 yr were 6.4 and 27.5%. There were 14 rainy events generated

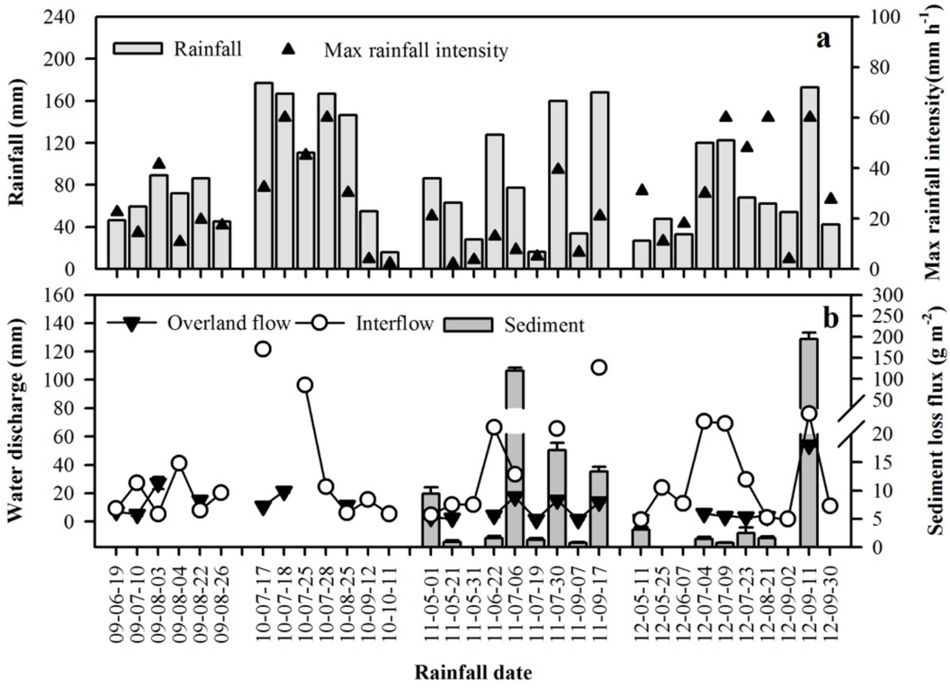

Fig. 3. (a) Rainfall, (b) hydrological characteristics and sediment yields during each rain event from 2009 to 2012. The sediment data from 2009 and 2010 were lost. Vertical bars indicate the standard deviations calculated from three replicates.

sediment ranged from 0.7 to 194.2 g m^{-2}. The average sediment loss fluxes in 2011 and 2012 were 20.4 ± 1.5 and 33.9 ± 3.0 g m^{-2}, and the annual cumulative sediment loss fluxes in 2011 and 2012 were 163.5 ± 11.7 and 203.5 ± 17.6 g m^{-2} (average, 183.5 ± 14.6 g m^{-2}), which is consistent with the standards for classification and the gradation of soil erosion of China (Ministry of Water Resources, The People's Republic of China, 2008). The site with a slope of 6.5° is classified as having a slight erosion risk (below 200 g m^{-2} yr^{-1}) according to the standard. The monitoring result of soil erosion is comparable and similar to other reports of runoff plot studies in this area (Zhu et al., 2002).

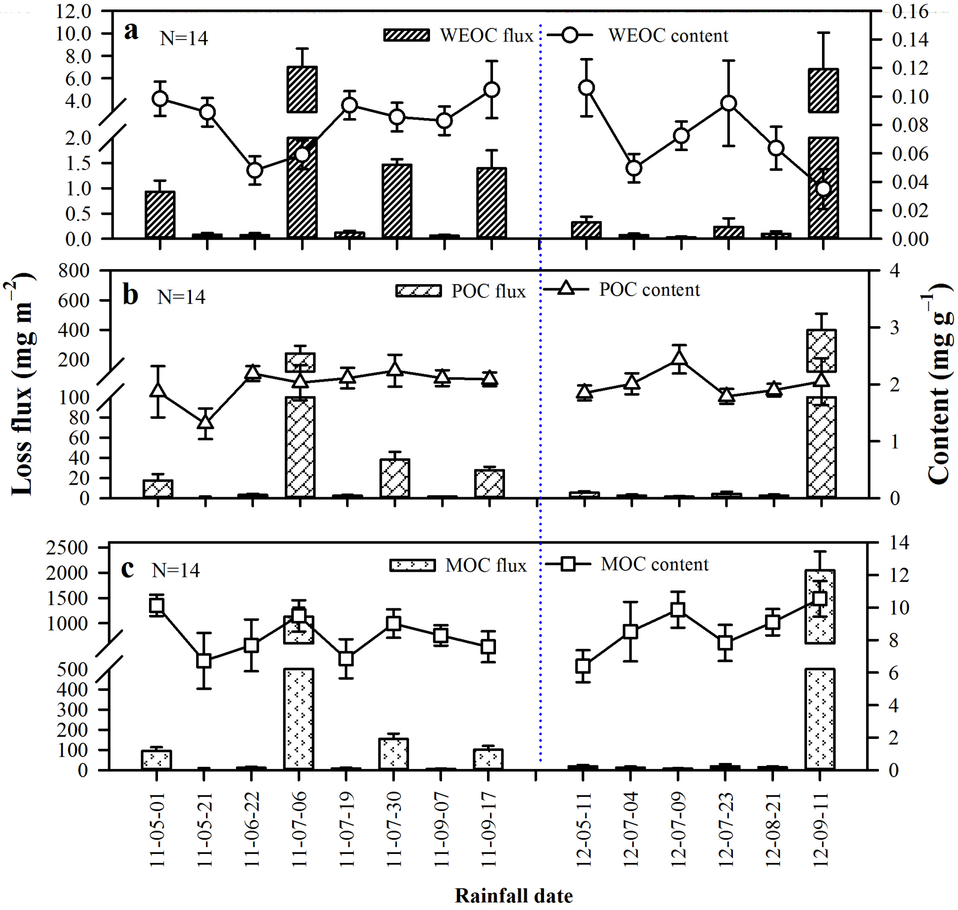

Fig. 4. Organic carbon contents and fluxes in sediments from 2011 to 2012. The sediment data from 2009 and 2010 were lost; thus, no relevant organic C loss data were obtained for 2009 and 2010. Water extractable organic carbon (WEOC), particulate organic carbon (POC) and mineral-associated organic carbon (MOC). Vertical bars indicate the standard deviations calculated from three replicates.

Forms and Fluxes of Soil Organic Carbon Loss Via Soil Erosion

The average WEOC effluxes in the sediment for each rainfall event were 1.4 ± 0.3 and 1.3 ± 0.6 mg m^{-2}, respectively (Fig. 4). The annual cumulative WEOC loss fluxes via sediment varied between 11.2 ± 2.4 and 7.6 ± 3.6 mg m^{-2} (average, 9.4 ± 3.0 mg m^{-2}). The POC contents in the sediments ranged from 1.3 ± 0.3 mg g^{-1} to 2.4 ± 0.3 mg g^{-1}, and the POC effluxes via sediment ranged from 1.2 ± 0.6 mg m^{-2} to 398.2 ± 110.9 mg m^{-2} for each rain event. The average POC effluxes via sediments in 2011 and 2012 were 41.8 ± 9.0 and 69.3 ± 19.4 mg m^{-2} per rain event, respectively. The annual cumulative POC loss fluxes via sediment varied between 334.5 ± 72.5 and 415.9 ± 116.7 mg m^{-2} (average, 375.2 ± 94.6 mg m^{-2}). Similarly, the MOC effluxes via sediment ranged from 6.2 ± 3.5 mg m^{-2} to 2046.2 ± 373.5 mg m^{-2} per event, and the average MOC effluxes via sediment in 2011 and 2012 were 189.3 ± 32.6 and 353.1 ± 67.1 mg m^{-2}, respectively. The annual cumulative MOC loss fluxes via sediment were 1514.1 ± 260.9 and 2118.7 ± 402.6 mg m^{-2} (average of 1816.4 ± 331.8 mg m^{-2}), which indicated that MOC was the dominant form of organic C lost via sediment and that WEOC only accounted for a small portion (0.4%) of the organic C lost.

Cumulative Dissolved Organic Carbon Loss fluxes via Overland Flow and Interflow

The annual cumulative DOC loss fluxes via overland flow in 2009, 2010, 2011, and 2012 were 144.4 ± 46.3, 171.2 ± 29.4, 169.8 ± 28.2, and 149.8 ± 27.9 mg m^{-2}, respectively (average of 158.8 ± 33.0 mg m^{-2}; Fig. 5). Similarly, the corresponding annual cumulative DOC loss fluxes via interflow were 356.5 ± 69.8, 782.1 ± 82.4, 1054.3 ± 84.9, and 808.8 ± 80.2 mg m^{-2}, and the average annual cumulative DOC loss flux via interflow for the 4-yr period was 750.4 ± 79.3 mg m^{-2}. Overall, the DOC

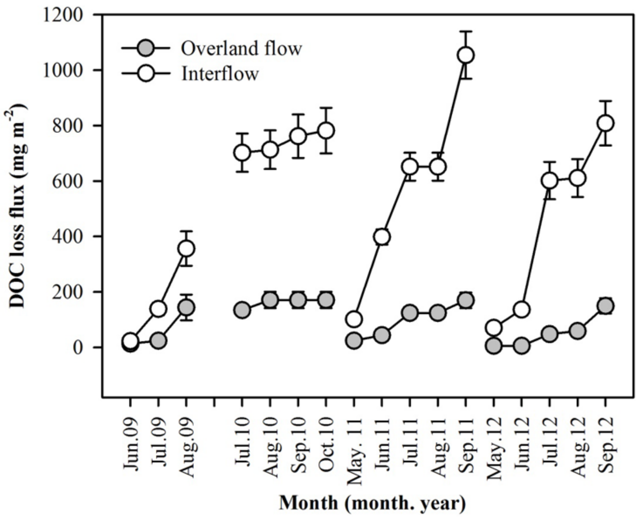

Fig. 5. Cumulative dissolved organic carbon (DOC) loss fluxes via overland flow and interflow from 2009 to 2012. Vertical bars indicate the standard deviations of three different replicates.

loss via interflow was approximately five times greater than the DOC loss via overland flow.

Relationships between Hydrologic Drivers and Soil Organic Carbon Lateral Transport

Sediment flux is the dominant factor controlling SOC loss via soil erosion ($R = 0.96$, Fig. 6a), and interflow discharge is the most important factor controlling DOC loss via interflow ($R = 0.99$, Fig. 6b). The amount of laterally transported SOC greatly depends on hydrological routes and the locations of water discharge. The characteristics of rainfall (i.e., rainfall and maximum rainfall intensity) were strongly related to the MOC contents in the sediment. This relationship could be described by a significant positive linear function ($R = 0.60$ and 0.52 in Fig. 6c and d, respectively). By contrast, the DOC concentration via interflow was significantly and negatively correlated with the amount of rainfall ($R = -0.46$ in Fig. 6e) but not the maximum rainfall intensity.

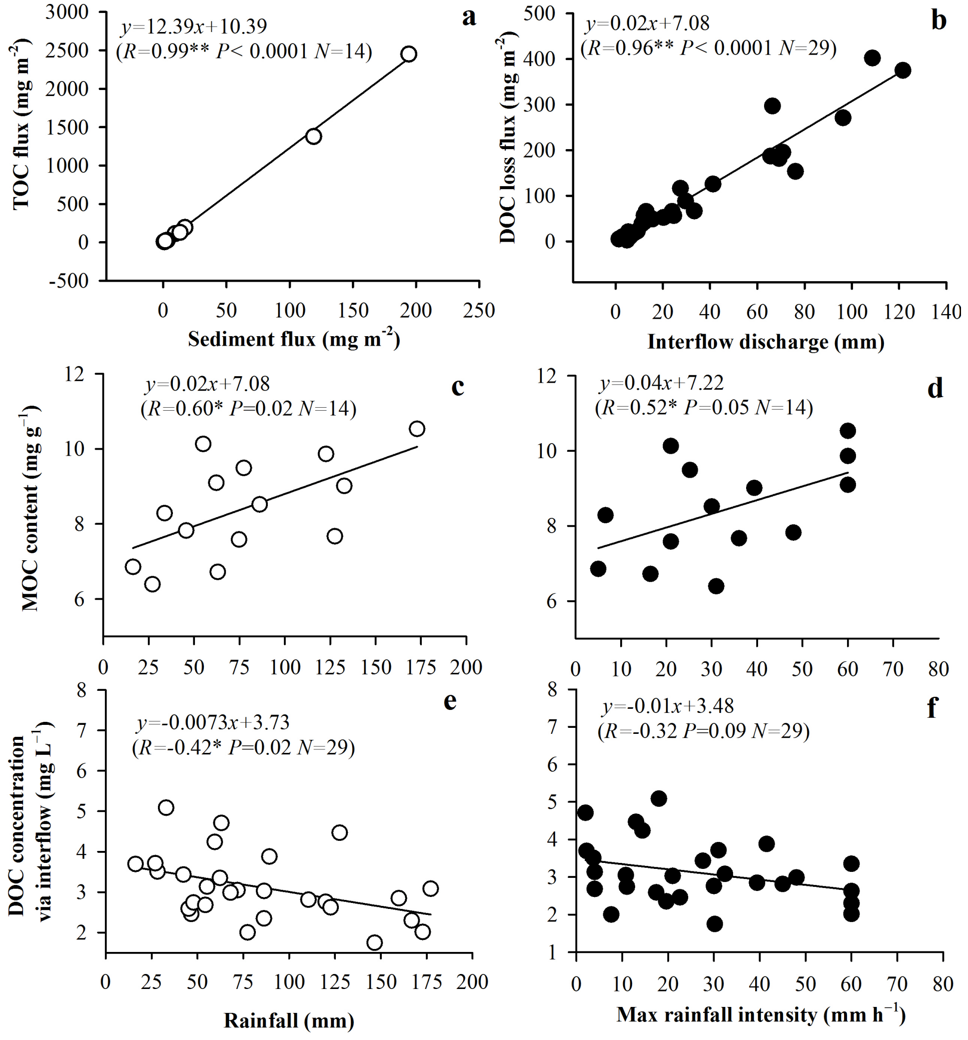

Fig. 6. Relationships between hydrologic drivers and lateral soil organic carbon (SOC) transport. Total organic carbon (TOC), Dissolved organic carbon (DOC), and mineral-associated organic carbon (MOC). * and ** are significant levels at $P < 0.05$ and 0.01.

DISCUSSION

Interflow is a Crucial Route of Lateral Soil Organic Carbon Transport

Current findings indicate that 2.2 ± 0.4 g m^{-2} yr^{-1} of SOC is lost due to erosion (Table 1), which accounts for 71% of the total SOC loss and indicates that soil erosion is the dominant hydrological route for lateral SOC transport. Similarly, previous studies have indicated that soil erosion is a major hydrological route for the lateral transport of SOC (Lal, 2003; Cohen et al., 2005). For example, Van Oost et al. (2007) reported that the average SOC loss flux via erosion was 3.4 ± 2 g m^{-2} yr^{-1} in agricultural soils from a large-scale survey of the world, which is consistent with our results.

Apart from soil erosion, DOC leaching is another important hydrological route for SOC loss, which results in decreased terrestrial organic C storage and plays a major role in organic C sequestration (Rumpel and Kögel-Knabner, 2011; Dlugoß et al., 2012; Ma et al., 2014). Kindler et al. (2011) argue that losses due to DOC leaching are comparatively small; however, DOC leaching is especially important in plot-scale studies due to the importance of DOC in the net ecosystem carbon balance of croplands. However, previous DOC leaching results mainly included isolated areas, and no information exists regarding the contributions of leaching to the total lateral transport of SOC. Interflow dominates the total runoff in the hillslopes of Regosol soil in Southwestern China (Zhu et al., 2009). Another key finding of this study is that interflow is a crucial but often ignored route of lateral SOC transport. The current findings clearly show that DOC leaching loss via interflow is 0.75 g m^{-2} yr^{-1} and that approximately 24% of the total SOC loss results from interflow (Table 1). This value is within the range of 1~20 g m^{-2} yr^{-1} previously observed in forest soils (Michalzik et al., 2001). However, our result is different from that (4.1 g m^{-2} yr^{-1}) reported by Kindler et al. (2011). Because DOC leaching is a complicated soil physical processes that results from the production, adsorption and desorption of DOC in soil (Kalbitz et al., 2000; Fujii et al., 2009), the amount of DOC lost through leaching varies greatly, mainly due to differences in the water flux and

Table 1. Organic C loss fluxes (mg m^{-2}) and contribution ratio (%) of overland flow, interflow, and soil erosion for total SOC loss on hillslope cropland.†

	Overland flow		Interflow		Soil erosion				
Year	DOC	Ratio	DOC	Ratio	WEOC	POC	MOC	Ratio	Total
2009	144.4 ± 46.3	–	356.5 ± 69.8		–	–	–	–	–
2010	171.2 ± 29.4	–	782.1 ± 82.4	–	–	–	–	–	–
2011	169.8 ± 28.2	–	1054.3 ± 84.9	–	11.2 ± 2.4	334.5 ± 72.1	1514.1 ± 260.9	–	–
2012	149.8 ± 27.9	–	808.8 ± 80.2	–	7.6 ± 3.6	415.9 ± 116.7	2118.7 ± 402.6	–	–
Mean	158.8 ± 33.0	5.1	750.4 ± 79.3	24.1	9.4 ± 3.0	375.2 ± 94.4	1816.4 ± 331.8	70.8	3110.2 ± 541.5

† Mean ± SD; Dissolved organic carbon (DOC), water extractable organic carbon (WEOC), particulate organic carbon (POC) and mineral-associated organic carbon (MOC).

DOC concentrations resulting from the rainfall, vegetation, soil texture, bedrock, and slopes in different ecosystems. Kindler et al. (2011) reported a mean annual water flux of 1013 mm and DOC concentrations of <4.0 mg L^{-1} in soil water from croplands receiving natural rainfall. Similar to previous results, the average annual water discharge was much lower than 245 mm and the DOC concentration was 3.1 mg L^{-1} in the interflow in this study.

Moreover, the total DOC loss (overland flow, interflow, and soil erosion including WEOC) accounted for 30% of the total SOC loss (Table 1 and Fig. 7). These results suggest that this DOC loss should not be neglected because of its considerable environmental influence on water bodies (Luo et al., 2009; Stutter et al., 2013). Regosols are an important land resource in the upper reaches of the Yangtze River, particularly in the Sichuan Basin, which covers an area of 160,000 km^2 and where 68% of the total croplands contain Regosols. Large DOC losses could affect the local water quality in the Three Gorges Reservoir. Hence, the loss of DOC via interflow should be considered. Additional research is needed to develop appropriate management practices for reducing DOC leaching via interflow in hillslopes with Regosols.

The Influences of Soil Erosion and Interflow on Soil Organic Carbon Sequestration

The loss of SOC through hydrological processes is important for SOC sequestration (Van Oost et al., 2007). Soil erosion is a ubiquitous process that plays a major role in SOC losses in croplands (Harden et al., 1999; Berhe and Kleber, 2013). In addition, soil erosion is a major variable that influences the export of SOC in topsoil, thereby preventing SOC sequestration in hillsides. This study shows that sediment yield is a dominant factor that controls SOC loss due to soil erosion (Fig. 6a), which indicates that controlling sediment is a direct method for mitigating SOC loss via soil erosion. Similarly, interflow discharge was an important factor controlling DOC leaching loss (Fig. 6b). As previously mentioned, interflow is a prevailing phenomenon because of the soil–bedrock interface in the hilly area, a characteristic that varies from other sloping croplands (Zhu et al., 2009) and plays an important role in the loss of SOC in hillslopes (Dlugoß et al., 2012; Rumpel and Kögel-Knabner, 2011). In the study area, soil erosion and interflow usually occurred simultaneously in the hillslopes during the rainy season, which indicated that controlling the later transport of SOC via sediment and interflow discharge is a key mechanism for mitigating SOC loss and enhancing organic C sequestration in hillslopes. Consequently, it was concluded that long-term SOC losses via soil erosion and interflow are important processes that restrict SOC sequestration, which likely results in low SOC level in the hilly area. Several soil conservation measures, such as terraced tillage, ridge-furrow cropping, and contour farming should be conducted to mitigate soil erosion. Meanwhile, we should seek agricultural management to reduce interflow discharge in areas with Regosols when designing a preferable SOC sequestration management strategy in the future.

Factors Influencing Mineralized-Associated Organic Carbon and Dissolved Organic Carbon Loss

The characteristics of rainfall (i.e., rainfall and maximum rainfall intensity) are significantly related to the MOC content and could be described by a positive linear function (Fig. 6c and d). This phenomenon can be explained by the mechanisms of rainfall and soil erosion interactions. Greater intensity rainfall provides more energy for destroying soil structure and carries clays from the soil surface, thereby enriching the amount of MOC (Schiettecatte et al., 2008; Shi et al., 2011). In contrast with MOC losses, the DOC concentrations via interflow showed significant negative and linear relationships with

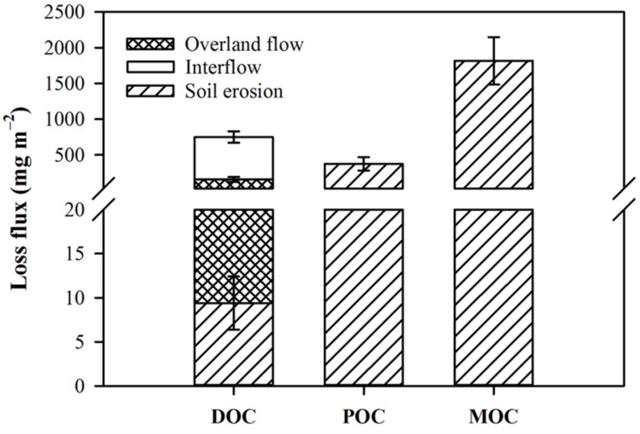

Fig. 7. Average annual DOC (including WEOC), POC, and MOC loss fluxes during the four rainy seasons from 2009 to 2012. Water-extractable organic carbon (WEOC), dissolved organic carbon (DOC), particulate organic carbon (POC), and mineral-associated organic carbon (MOC). The vertical bars indicate the standard deviations calculated from three replicates.

rainfall (Fig. 6e). This finding contradicts previous field and laboratory results in which that the DOC concentration was positively correlated with rainfall. These studies stipulated that increasing rainfall and greater soil moisture enhance microbial activity, particularly in well-drained soils, which improves the DOC concentrations (Fröberg et al., 2006). On the hillslopes of croplands composed of Regosols, continuous interflow of water via macrospores in soils under heavy rainfall events may not allow adequate contact time between the water and soil to release and flush out a substantial amount of DOC (Dosskey and Bertsch, 1997). This phenomenon decreases the DOC concentrations in the interflow under heavy rainfall, indicating that rainfall is a key negative regulatory factor that influences the DOC concentrations in the interflow water.

CONCLUSIONS

This study showed that overland flow, interflow, and soil erosion accounted for 5, 24, and 71%, respectively, of the annual cumulative total SOC loss. Mineral-associated organic carbon is the main form of SOC that is transported laterally, and DOC is another important component. Interflow is an important hydrological route of lateral SOC transport but is usually neglected or underestimated. Dissolved organic carbon leaching via interflow is an important mechanism of SOC loss. Thus, DOC transport via interflow should be subjected for further research to mitigate SOC loss and enhance organic C sequestration on hillslope landscapes.

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