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Leaching is the dominant route for soil organic carbon lateral transport under crop straw addition on sloping croplands

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ABSTRACT

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Few field data sets are available that systematically measure soil organic carbon (SOC) transport via surface runoff, leaching and soil erosion under crop straw applications. Therefore, organic carbon (C) loss fluxes via the three routes were simultaneously observed from 2010 to 2012 based on a crop straw addition experiment. This study included three treatments: CK (no fertilizer); RSD (crop straw addition) and RSDNPK (crop straw addition combined with mineral fertilizers). As compared with CK treatment, annual dissolved organic C (DOC) loss caused by surface runoff under RSD and RSDNPK treatments decreased significantly ($P < 0.05$) by 302.8% and 294.2%. Similarly, corresponding organic C loss caused by soil erosion reduced sharply by 638.8% and 1227.3%. In contrast, corresponding annual DOC leaching fluxes increased significantly ($P < 0.05$) by 133.3% and 109.3%. Overall, the total fluxes of SOC transport under RSD and RSDNPK treatments decreased significantly ($P < 0.05$) by 132.3% and 184.1% compared with CK treatment (4975.7 ± 1207.8 mg/m^2). DOC leaching accounted for 70% and 77% of SOC transport under RSD and RSDNPK treatments. These results clearly show that leaching is the dominant route of SOC lateral transport under crop straw applications. Therefore, reduced DOC leaching is the crucial link to enhance SOC sequestration when crop straw is returned to sloping croplands.

Keywords: hydrology route; dissolved organic carbon loss; crop straw returned; fertilization experiment; hillslopes

Soil organic carbon (SOC) lateral transport is a pivotal process of SOC loss, which plays a significant role in SOC sequestration (Lal 2005, Pospíšilová et al. 2011) and water environment quality (Krasner et al. 2009). Fertilization, especially crop straw application, is an effective practice that affects the quantity and quality of SOC and influences hydrologic characteristics, thereby having an impact on the process of SOC lateral transport.

Over the past decades, many studies have confirmed that crop straw combined with mineral fertilizers is an effective agronomic way to sustain grain yield and reduce runoff losses (Kaewpradit et al. 2009). Leaching is not a crucial problem for SOC only, but leaching of nutrients, mainly nitrates, has negative consequences for environment, too (Elbl et al. 2014, Plošek et al. 2017). Fertilization, especially for crop straw addition, has a substantial effect on soil physicochemical property and hydrologic characteristics, thereby influencing SOC losses via runoff and leaching. For instance, Prosdocimi et al. (2016) confirmed that crop straw mulching is effective in decreas-

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ing sediment yield and surface runoff discharge, which is achieved immediately after crop straw application. Similarly, Rahma et al. (2017) reported that crop straw mulched in the topsoil reduced the amount of soil erosion from hillslope croplands under extreme rainfall events. Shi and Schulin (2018) reported that crop straw application resulted in a decrease in organic carbon (C) loss through an artificial rainfall experiment. In general, most of these studies, however, only considered the effects of crop straw additions or mulching on SOC transport in isolated situations (e.g., through soil erosion alone). Thus, an accurate amount of SOC lateral transport caused by surface runoff, leaching, and soil erosion under crop straw application has not been reported. The magnitude and dominant hydrological route for SOC transport under crop straw applications remain uncertain.

The hillslope croplands of Regosols in the Sichuan Basin of China are distributed widely and have been extensively degraded by severe soil erosion. Regosols, which are characterized by thin soil layers, are easily saturated during precipitation. Leaching is a major phenomenon that occurs primarily during the rainy season (Zhu et al. 2009). Hence, surface runoff, leaching, and soil erosion occur simultaneously on hillslope croplands during the rainy season. The present study simultaneously monitored SOC lateral transport losses caused by surface runoff, leaching, and soil erosion based on a field lysimeter experiment from 2010 to 2012. The specific objectives of this study were to (1) quantify the organic C loss fluxes from surface runoff, leaching, and soil erosion; (2) evaluate the effect of crop straw applications on SOC lateral transport flux; (3) identify the dominant route of SOC lateral transport under crop straw application.

MATERIAL AND METHODS

Site and soil description. The experiment was set up in the central Sichuan Basin of China, which is located at 31°16'N, 105°28'E, and it has a subtropical climate. The amounts of annual precipitation from 2010 to 2012 were 892, 1061 and 1080 mm, respectively. Based on the World Reference Base for Soil Resources (IUSS Working Group WRB 2006), the tested soil is classified as a Regosol. The soil which was developed from purplish shale has the typical 'binary structure of soil-bedrock'. The specific soil used is a silty loam soil with a pH of 8.3, bulk density of 1.3 g/cm^3, organic carbon content of 5.1 g/kg, total nitrogen content of 0.6 g/kg, total phosphorus content of 0.6 g/kg, field capacity of 27.3%, and saturated hydraulic conductivity of 16.8 mm/h (Zhu et al. 2009).

Experimental setup. According to the Handbook of Water and Soil Conservation Monitoring in Runoff Plots and Small Watersheds (Ministry of Water Resources, PRC 2015), the field plots were constructed as free-draining lysimeters. The experimental lysimeter plots (size: 8 × 4 m^2, slope: 7%), allowed for the simultaneous measurement of surface runoff, leaching, and soil erosion. These free-draining lysimeters were placed by excavating the soil to the bedrock and constructed the lysimeters for hydrological isolation in 2002 (Zhu et al. 2009). Each plot was hydrologically isolated by walls filled with cement that reached the bedrock and extended to a depth of at least 0.6 m to prevent lateral seepage from adjacent plots according to Patent No. ZL2007100640686.

The plots were laid in the experiment in a randomized block design with three replicates. One control and two fertilizer treatments were used: no fertilizer (CK); crop straw addition (40% of applied nitrogen, RSD), and crop residue (40% of applied nitrogen) combined with mineral nitrogen (60% of applied nitrogen; RSDNPK). All the crop straws were collected from nearby croplands of local

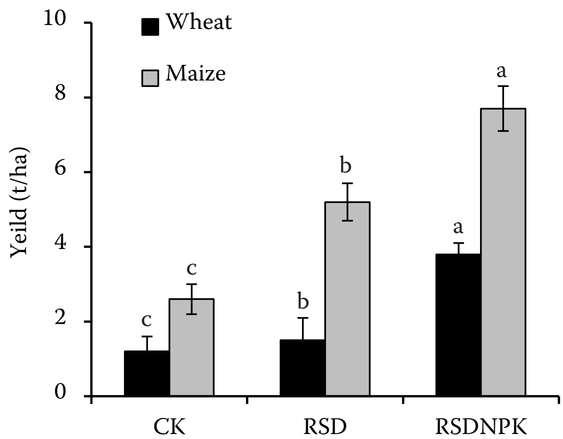

Figure 1. Average yields of wheat and maize under different fertilization treatments from 2010 to 2012. Vertical bars indicate the standard deviations of three different replicates. The lowercase letters indicate significant differences (P < 0.05, least significant difference) among all the treatments. CK – no fertilizer; RSD – crop straw addition; RSDNPK – crop straw addition combined with mineral fertilizers

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farmers. 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. 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. RSDNPK treatments in this study received equal nitrogen amounts of 280 kg N/ha/year (in terms of mass, that is, 130 kg N/ha in the wheat season and 150 kg N/ha in the maize season). In the RSD and RSDNPK treatments, the wheat or maize growing seasons were applied at rates of 6000 and 7000 kg/ha maize or wheat straw, respectively. All the straws were cut into small pieces approximately 5 cm long, then returning to soil. RSDNPK treatment received ammonium bicarbonate (78 kg N/ha in the wheat season and 90 kg N/ha in the maize season), triple

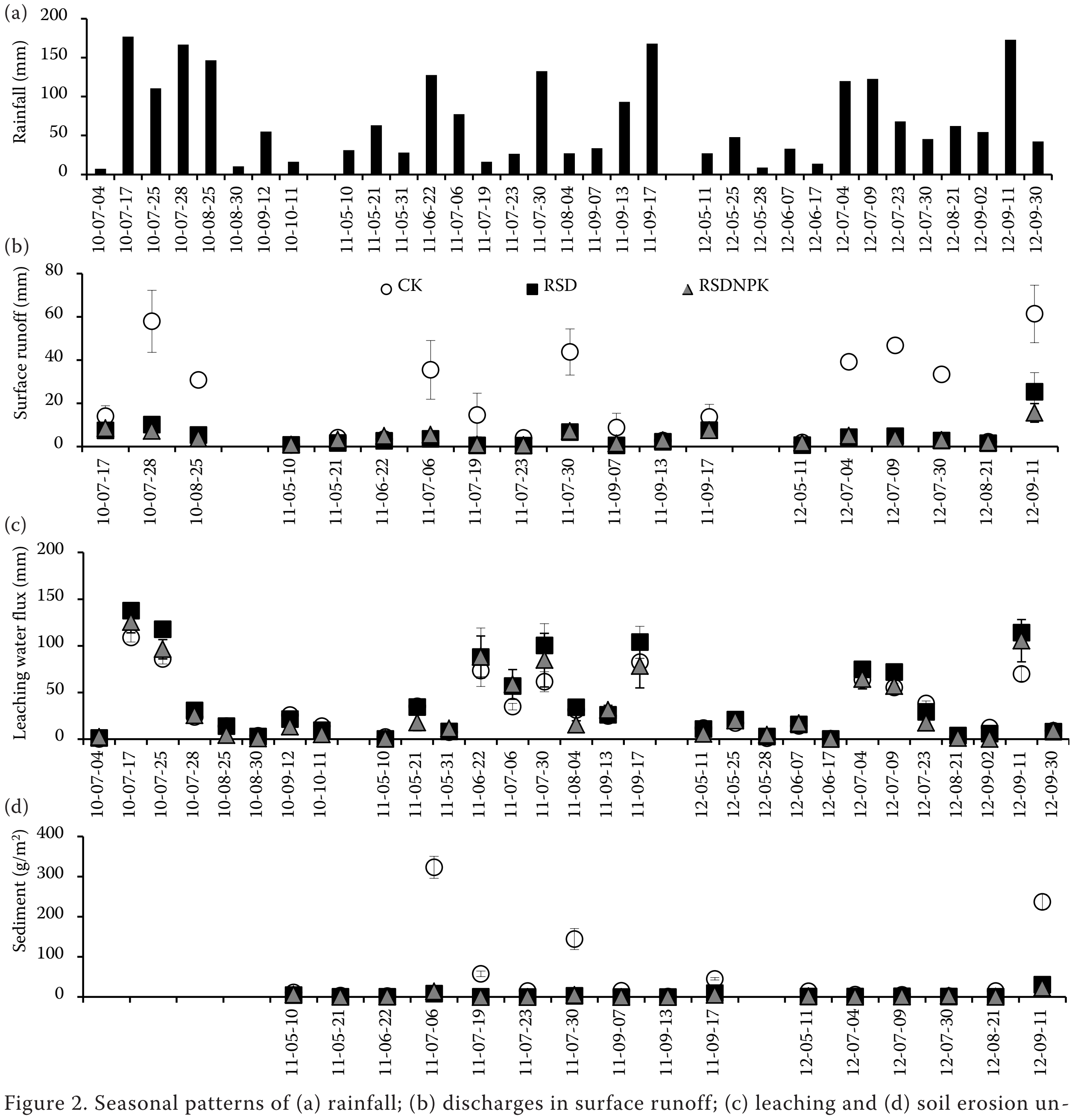

Figure 2. Seasonal patterns of (a) rainfall; (b) discharges in surface runoff; (c) leaching and (d) soil erosion under different fertilization treatments from 2010 to 2012. Vertical bars indicate the standard deviations of three different replicates. CK – no fertilizer; RSD – crop straw addition; RSDNPK – crop straw addition combined with mineral fertilizers

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superphosphate (32 kg P/ha equivalent in the wheat or maize season) and potassium chloride (30 kg K/ha equivalent in the wheat or maize season) as basal fertilization. All of the mineral fertilizers and crop straw were applied by hand as basal fertilization on the same day as seeding.

Runoff discharge measurement and water sampling. Surface runoff and leaching water were collected by buckets. Surface runoff and leaching water samples were collected separately from the different buckets. Polyethylene bottles (500 mL) were used to collect water samples to determine the dissolved organic carbon (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 Al K $(SO_4)_2 \times 12\ H_2O$ solution to promote coagulation. When the sediment settled, the excess water was decanted and dried and the remaining soil was weighed at 105°C (Polyakov and Lal 2008).

Analytical methods. The water samples of the surface runoff or leaching were passed through 0.45 μm filter membranes to analyze the DOC concentrations using AA3-Auto-analyzer (Bran + Lubbe, Norderstedt, Germany). The organic carbon (OC) content in the sediment was measured using the wet combustion method in 133 mmol/L $K_2Cr_2O_7$ at 180°C for 5 min, followed by titration of the digests with iron (II) sulfate ($FeSO_4$; Blair et al. 1995). All of 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.

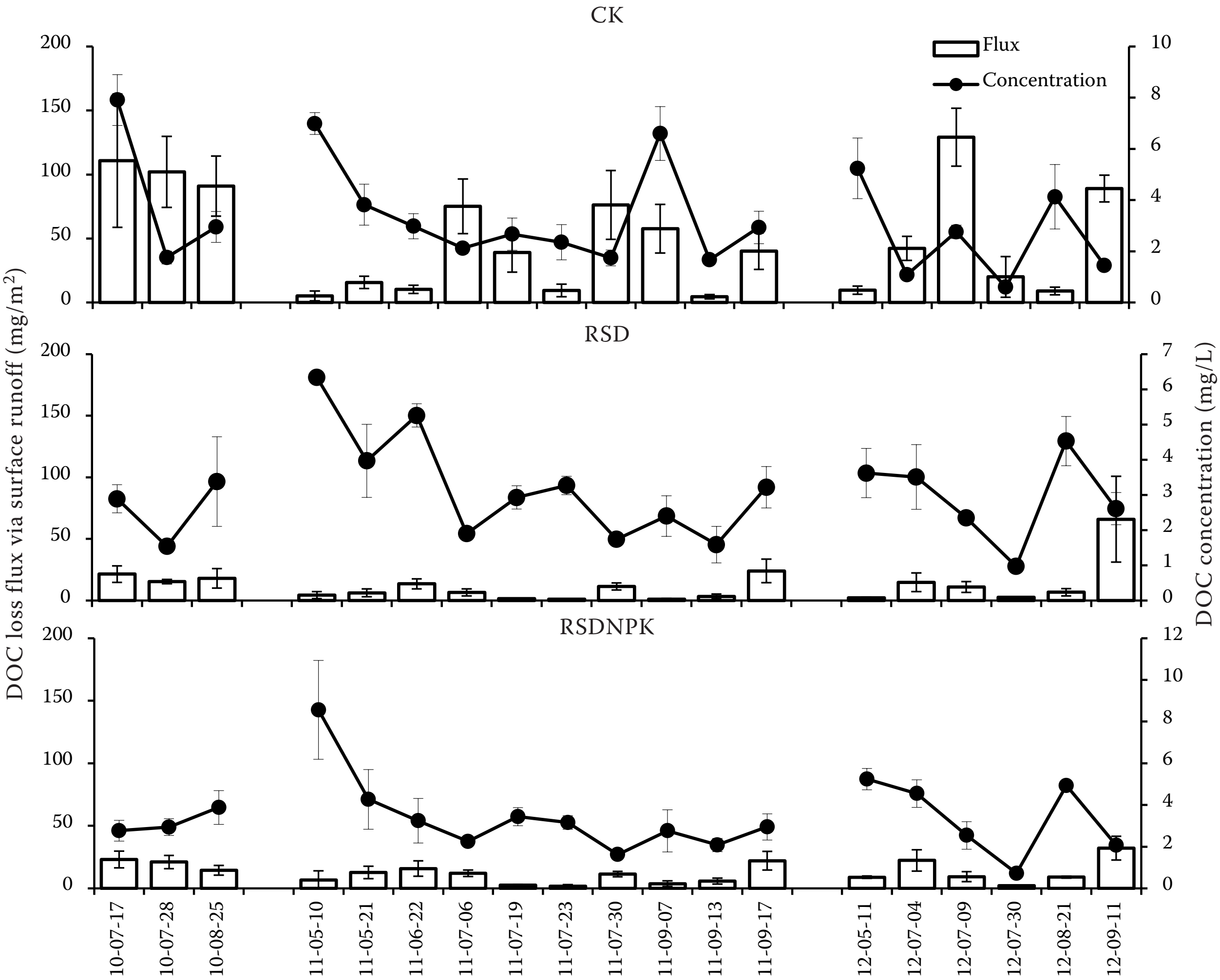

Figure 3. Seasonal patterns of dissolved organic carbon (DOC) concentration and loss flux via surface runoff for all treatments from 2010 to 2012. Vertical bars indicate the standard deviations of three different replicates. CK – no fertilizer; RSD – crop straw addition; RSDNPK – crop straw addition combined with mineral fertilizers

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Data analysis. DOC loss flux during an individual flow (Q_i) produced from a rainfall event was calculated as follows:

$$Q_i = C_i \times q_i \quad (1)$$

Where: Q_i – DOC loss flux in surface runoff or leaching (mg/m^2); C_i – DOC concentration in surface runoff or leaching water (mg/L); q_i – runoff depth per unit (mm).

The OC loss flux in the sediments during an individual flow (Q_{Si}) was calculated as follows:

$$Q_{Si} = C_{si} \times q_{si} \quad (2)$$

Where: Q_{Si} – OC loss flux (mg/m^2); C_{si} – OC content (g/kg); q_{si} – sediment loss flux (g/m^2).

The annual cumulative DOC and OC loss fluxes were calculated as follows:

$$Q = \sum_{i=1}^{n} Q_i \quad (3)$$

Where: Q – annual cumulative loss flux (mg/m^2), $i = 1 \sim n$ (n – number of runoff events in a given year).

The statistical analyses and graphs preparing were used the SPSS 19.0 (SPSS, Inc., USA) and Sigma plot 10.0 software (Systat Software, Inc., Chicago, USA) packages.

RESULTS AND DISCUSSION

Crop yield, rainfall, runoff discharge and sediment flux. Average annual yields for wheat and maize under CK treatment were 1.2 ± 0.4 and 2.6 ± 0.4 t/ha. The corresponding yields under RSD and RSDNPK treatments were significantly increased by 25.0, 216.7, 100.0 and 196.2%, respectively, compared with CK treatment (Figure 1). There were 33 rainfall events observed, which were

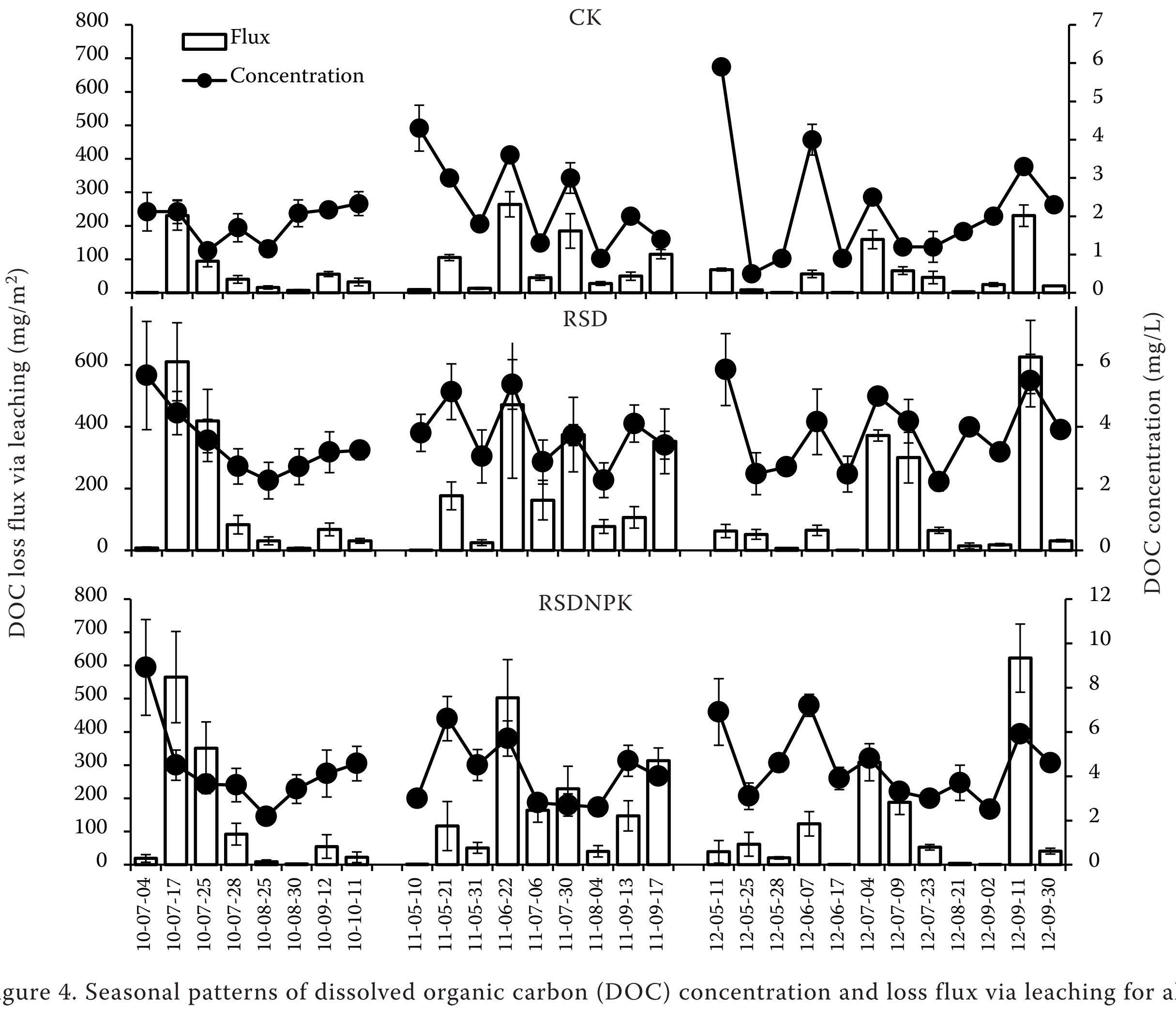

Figure 4. Seasonal patterns of dissolved organic carbon (DOC) concentration and loss flux via leaching for all the treatments from 2010 to 2012. Vertical bars indicate the standard deviations of three different replicates. CK – no fertilizer; RSD – crop straw addition; RSDNPK – crop straw addition combined with mineral fertilizers

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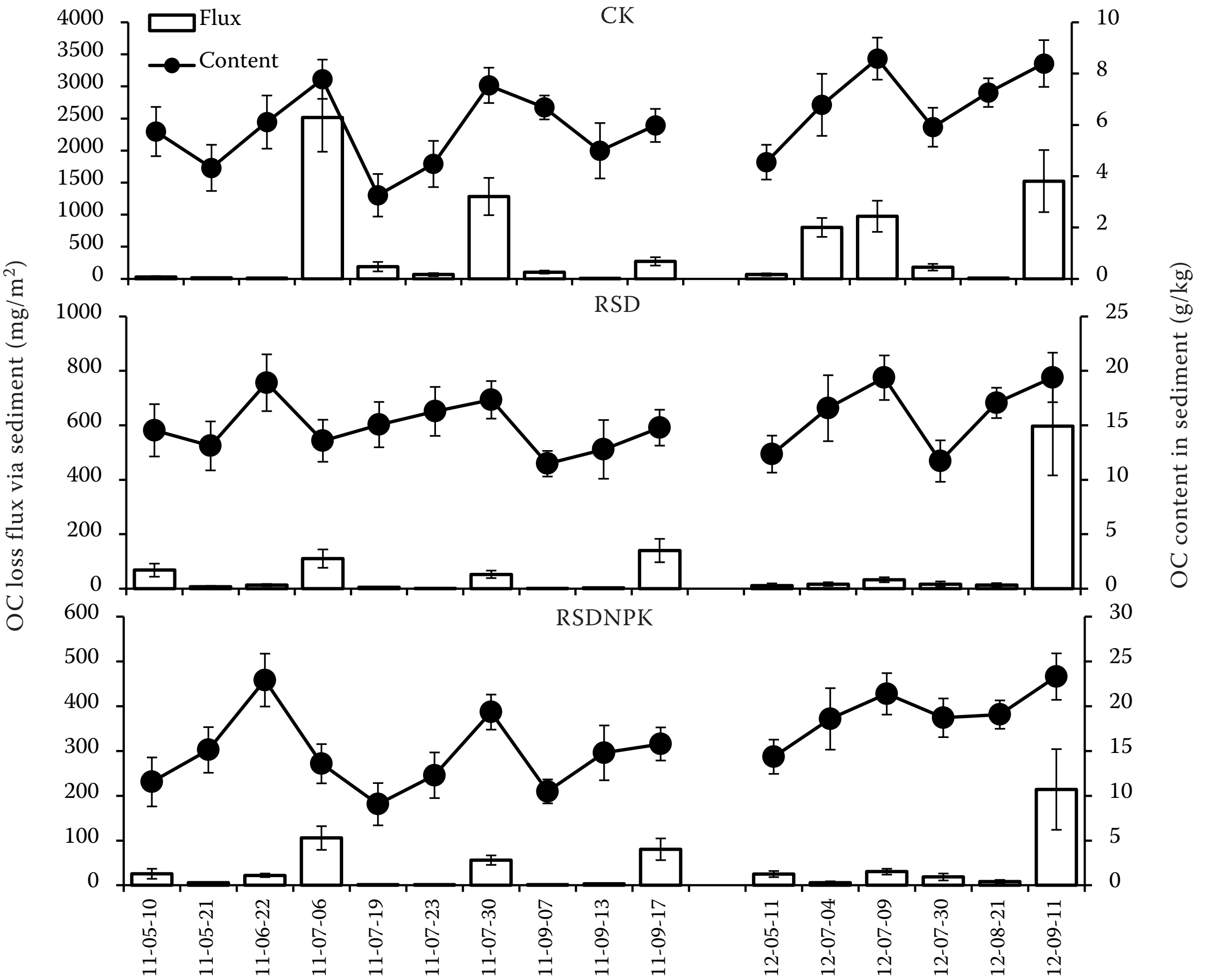

Figure 5. Seasonal patterns of organic carbon (OC) content and loss fluxes caused by soil erosion for all treatments from 2010 to 2012. Vertical bars indicate the standard deviations of three different replicates. CK – no fertilizer; RSD – crop straw addition; RSDNPK – crop straw addition combined with mineral fertilizers

ranged from 10.5 to 177.1 mm per event (Figure 2). The average annual cumulative surface runoff discharges for the CK, RSD and RSDNPK treatments were 139.5 ± 18.3, 29.3 ± 6.6, and 27.9 ± 4.3 mm, respectively. Average annual cumulative values of sediment fluxes were 549.9 ± 72.6, 32.0 ± 6.3, 17.1 ± 3.2 g/m^2, respectively. Compared with CK treatment, sediment yield under RSD and RSDNPK treatments were sharply decreased by 1618.4% and 2215.8%. These findings are consistent with the results of Won et al. (2012). Because the pores in the soil surface under crop residue mulching are protected from clogging by small clumps of soil and organic particles that detach from the soil matrix by raindrop impact (Wei et al. 2017). Moreover, crop straw application also can effectively increase crop biomass, plant coverage and water consumption, thereby decreased surface runoff and sediment. Discharges caused by leaching were increased by 23.7% and 3.9% under RSD and RSDNPK treatments compared with CK treatment, which was due to crop straw enhancing infiltration (Peng et al. 2016).

DOC loss caused by surface runoff and leaching. Average annual cumulative DOC loss fluxes caused by surface runoff in CK, RSD and RSDNPK treatments were 311.8 ± 94.5, 77.4 ± 32.0, and 79.1 ± 25.7 mg/m^2, respectively (Figure 3). Compared with CK treatment (2.15 ± 0.21 mg/L), the mean values of DOC leaching concentrations in RSD and RSDNPK treatments increased significantly ($P < 0.05$) by 71.7% and 100.5% (Figure 4). DOC leaching is a complicated biochemical process which is caused by adsorption and desorption of soil DOC (Kalbitz et al. 2000). Soil DOC mainly originates from plant litter or root exudates, soil humus, and

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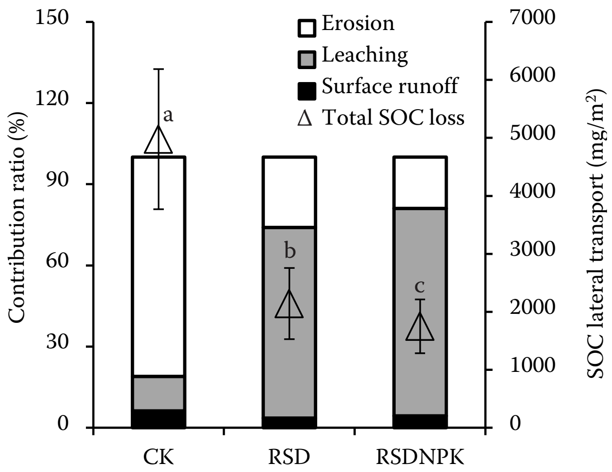

Figure 6. Contribution of surface runoff, leaching and soil erosion for soil organic carbon (SOC) lateral transport. Vertical bars indicate the standard deviations of three different replicates. The lowercase letters indicate significant differences ($P < 0.05$, least significant difference) among all the treatments. CK – no fertilizer; RSD – crop straw addition; RSDNPK – crop straw addition combined with mineral fertilizers

various exogenous organic matter inputs, which is greatly enhanced by crop straw application (Gong et al. 2009, Torma et al. 2018). Consequently, the DOC concentration in the leakage water for the crop straw application was significantly greater in contrast to no fertilizers application. Additionally, the lowest cumulative DOC leaching loss was found in CK treatment (660.4 ± 118.3 mg/m^2) whereas the highest was observed in the RSD treatment (1540.4 ± 415.2 mg/m^2). This value is similar to the results (1.3 g/m^2/year) under continuous rice cropping observed by He et al. (2017), whereas was much smaller than the loss of 3.7–51.1 g/m^2/year that Said-Pullicino et al. (2016) calculated for paddy-rice systems in Italy.

Organic C loss caused by soil erosion. The mean values of organic C (OC) content in the sediment for CK, RSD and RSDNPK treatments were 6.30 ± 0.83, 15.43 ± 2.07, and 16.86 ± 2.34 g/kg, respectively (Figure 5). Compared with CK treatment, the mean values of OC content in RSD and RSDNPK treatments increased significantly ($P < 0.05$) by 144.9% and 167.6%. Because soil erosion disturbs topsoil and preferentially removes SOC from upslope sites and sediments that primarily contain semistable or stable SOC are usually rich in fine silt and clay-size particles (Martínez-Mena et al. 2012). Crop straw application enhances SOC content in topsoil, thereby increasing organic carbon content in sediment. Compared with CK treatment (4026.7 ± 996.6 mg/m^2), OC loss flux caused by sediment for RSD and RSDNPK treatments decreased significantly ($P < 0.05$) by 638.8% and 1227.3%.

Contributions of surface runoff, leaching and soil erosion to SOC lateral transport. Annual cumulative SOC transport fluxes for CK, RSD and RSDNPK treatments were 4975.7 ± 1207.8, 2141.8 ± 613.3, and 1751.3 ± 462.8 mg/m^2, respectively (Figure 6). Soil erosion accounted for 81% of SOC lateral transport for CK treatment, which indicated that soil erosion is the major hydrological route for the lateral transport of SOC (Oost et al. 2007, Hua et al. 2016). However, DOC leaching accounted for 71% and 78% of SOC lateral transport under RSD and RSDNPK treatments, which suggested that leaching was the dominant hydrological route for SOC lateral transport under crop straw application. On the hillslopes, leaching is fundamentally important for reducing SOC lateral transport under crop straw applications. Therefore, reducing DOC leaching loss is essential to SOC sequestration when considering optimized management strategies of crop straw return.

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